HIGH-TENSION UNDERGROUND ELECTRIC CABLES

FLOY

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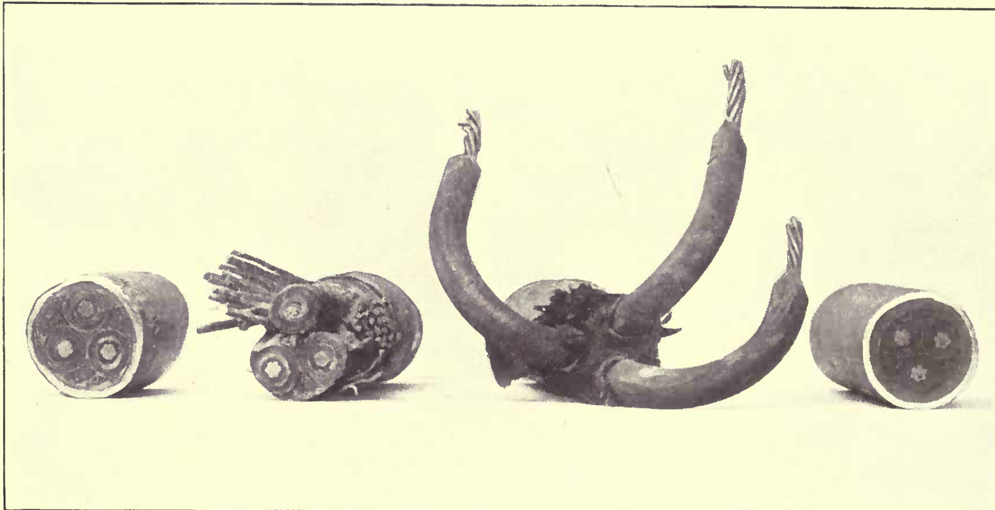

PIECES OF THE FIRST 25,000-VOLT UNDERGROUND CABLES.

These three-conductor, high-tension cables were installed at St Paul, Minn., in 1900, and are still in successful use. The highest potential used under ground prior to 1900, was 11,000 volts, since that date, 25,000 and 30,000-volt cables have been installed in a number of places.

HIGH-TENSION UNDERGROUND ELECTRIC CABLES

A Practical Treatise For Engineers

BY

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Etc.

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PREFACE.

As one of the experts in a recent and important controversy regarding the necessity of putting underground certain high-tension aerial wires in the largest city in America, the author was made to realize the general lack of information with reference to the possibilities and advantages of subsurface electric transmission. This led to the writing of a series of papers on high-tension cables, which were published in the Electrical World, during the fall of 1908. The interest displayed at this time, in these matters, has led the author to conclude that re-writing, expanding and adding to these papers so as to compile a summary of the high-tension cable situation as it exists to-day, would be a valuable and a helpful contribution to the up-to-date literature of electrical engineering.

In the following pages are contained summaries of experience, facts and figures, which have been gathered from almost innumerable sources, so that the whole may be said to fairly represent the concensus of present opinion of a majority of engineers acquainted with and practiced in the use of high-tension subsurface transmission.

After a brief explanation of the development of underground transmission, the verbatim opinions of experts using such method of operation are given; also

records made by various companies with a list of the more interesting high-tension cable installations, including potentials employed, thickness of insulations, sheaths and other data. The advantages of underground compared with aerial construction are brought out, followed by a discussion of the dielectrics employed and the present practical voltage limits attainable with electric underground transmission. Curves, tables and data are presented relating to the heating and testing of cables, as well as formulae to be used in electrical calculations. The book concludes with a chapter on the costs of underground installations with particular reference to the prices of cables.

The author desires to extend his thanks to those who have co-operated in his efforts to compile up-to-date knowledge and practice, and trusts that this little volume will prove of assistance to those who desire to acquaint themselves either with what is being done or what are the present possibilities of high-tension underground electric transmission.

HENRY FLOY.

City Investing Building,
New York, February 1, 1909.

Table of Contents.

CHAPTER VI, HEATING OF CABLES.

Chapter I.

INTRODUCTORY.

General. The use of aerial lines for transmission and distribution systems was logically to be expected in the early stages of electrical development on account of the simplicity and low cost of construction. With the development of the industry and the necessity of putting wires underground, continuously insulated conductors were undertaken, which, like many other innovations, proved in some cases unreliable and unsatisfactory at the beginning; but with the development of improved processes and greater perfectedness in manufacture, subsurface cables, even for high voltages, have come to be regarded as reliable as almost any other appliance employed in the electrical art.

In spite of the many instances of successful installation and operation of high-tension cables, both under ground and under water, there exists a general lack of information, and to some extent, a general prejudice, which prevents their wider use and installation.

The importance to the engineer of knowing the highest practical voltage at which subsurface cables can be successfully operated, the minimum insulation safely allowable for a given potential, and the cost of such cables completely installed, is not fully realized.

Knowledge, or lack of knowledge, of this subject on the part of the engineer in charge, may determine whether an alternating or a direct-current system of high or low voltage shall be selected for a given installation with consequent large or small expenditure in transformer plant, elaborate switchboard, enlarged buildings, or unnecessarily heavy insulation. The lack of general information regarding recent improvements made both in the manufacture of cables and in the solution of the peculiar troubles likely to arise in the operation of high-tension cables, probably accounts in a large measure for their comparatively limited use. There has existed no particularly urgent incentive for investigation as to the possibilities and advantages to be gained in the construction and use of high-tension cables. The operating companies, in order to avoid investment, have usually been opposed to, and in consequence have developed and used every argument against, underground construction. The cable manufacturers themselves, conceding the good work done by some of them, have been working along commercial rather than scientific lines, and the properties of the several dielectrics available for insulation have been considered from a commercial rather than an engineering standpoint. The manufacturers have hardly paid sufficient attention to the electric phenomena of dielectrics, a scientific study of which would doubtless have proved both interesting and remunerative. By way of illustration it may be said that few insulated wire manufacturers appreciate the difference, in their effect on

insulation, of alternating waves of various forms, or of the various processes used in the production of resin oil that result in oils, varying widely in value, for use as dielectrics. Recent research along these lines gives promise of far-reaching results that mark a decided advance in the use and the permanency of underground cables. It is only just recently for example, that one has been able to purchase paper cables, the flexibility of which remains practically unchanged at zero temperature.

It is now recognized that many dielectrics when freshly produced, make an excellent showing, but in the course of a few months or years, undergo physical or mechanical change which greatly depreciates their value or renders them worthless. Permanency has been generally admitted as the sine qua non of cable success, and this is now being obtained as a result of experiment and test. The only really valid objection that can to-day be urged against the use of underground cables is their relatively high cost as compared with aerial lines, but this objection decreases in almost direct proportion to the increase in the number of circuits installed. Attempts to meet this objection of initial expense have been made in several ways, primarily and most successfully by substituting a cheaper material, such as paper or cambric, for rubber insulation; and secondarily, by the construction of cheaper forms of conduits in which the cables are drawn or by the abandonment of conduits altogether, simply laying the cables in the ground—as is being done at pres-

ent; for example, by the New York Edison Company in city parks—or in some cases, where low potentials are used, embedding the bare conductor, in situ, in a cheap insulating material, usually a bitumen compound.

The practicability and reliability of cables for 110, 220, or even 500-volt service, is usually admitted; but when cables for higher potentials are considered it is often asserted that they are unreliable. Contradiction of such statements is best made by an examination of the records made by high-voltage underground systems, and the conclusion with regard thereto submitted by those having practical experience with such systems rather than by the consideration of statements of mere theorists or those not practically engaged in the transmission of electrical energy at high voltages underground, or those endeavoring to operate such systems who have not the education or experience qualifying them to do so successfully.

Historical. It is not perhaps generally appreciated that 26 years ago, underground cables laid in a trench filled with "Bitite," a vulcanized bitumen, were giving satisfactory service for low-voltage distribution in England, and that 25 years ago, Eastbourne, England, was lighted from the comparatively high-voltage circuits of the Brush Company which were contained in an underground system of iron pipes through which the conductors were drawn. Twenty years ago, 2000-volt underground cables were in use in Rome, Tivoli, Turin and Milan, while Berlin early had a reputation for its

underground system, and Paris began its subsurface distribution by installing copper bars supported on porcelain knobs in its sewers. The well-known 10,000-volt concentric cables of Ferranti were installed in London over 18 years ago and early proved the success of high-tension underground transmission. Cables with rubber insulation 4/32 inch thick covered with a lead sheath, operating on 7,500-volt arc light circuits, installed in Buffalo 17 years ago, are still in use. In 1889, New York City had many miles of low-tension underground cables and the city authorities, resorting to police methods, were cutting down aerial lines to force the companies underground. Since those days, marked advance has been made both in details of conduit construction and methods of cable manufacture.

Expert Opinions. The present status of high-tension underground distribution can be best learned from a consideration of the expressed opinions of some of the well-known members of the engineering profession who have attained and still hold their high positions, largely by reason of their successful operation of such high-tension systems. Mr. L. A. Ferguson, president of the American Institute of Electrical Engineers and vice-president of the Commonwealth Edison Company, Chicago, which company has a station generating capacity of 120,000 kw and operates both aerial and conduit systems including nearly 400 miles of 9,000 and 20,000-volt paper-insulated underground cable, in addition to much low-tension cable, succintly states the

superiority of subsurface conductors over aerial construction as follows:*

> "It is generally conceded that when the business will warrant the investment, electrical lines are much better underground than overhead."

An ex-president of the same Institute, Mr. H. G. Stott, chief engineer of the Interborough Rapid Transit Company—having 95,600-kw station capacity distributed wholly through 375 miles of 11,000-volt cables, some submarine—says:†

> "I think it dwells in the minds of many able engineers that high-tension lines are very dangerous. I differ from that. I think the high-tension underground cable is the safest thing we have—a great deal safer than low-tension."

Mr. J. W. Lieb, Jr., also ex-president of the American Institute of Electrical Engineers and general manager of the New York Edison Company—having 150,000 kw rated generating station capacity, or including storage batteries, 200,000 kw capacity—which company, in addition to many miles of low-tension cable, is operating over 200 miles of 6,600-volt cables, stated to the writer with reference to the high-tension cables, that,

> "There is no question as to the practicability and reliability of underground cables whether for low-tension or high-tension service, when compared with aerial conductors."

* Paper presented at the International Congress, St. Louis, 1904, entitled, "Underground Electrical Construction."

† Proceedings A. I. E. E., vol., XXI., page 443.

Warren Partridge, Engineer for the Public Service Corporation of New Jersey, says*

> "In spite of all difficulties experienced****** cable systems are fully as reliable as other elements in the electric power system. Our records for a period of three years show that cable breakdowns caused but 7 per cent of all interruptions to service and that the duration of time of cable interruptions was no longer than the average interruptions from other causes."

Many other less well-known but equally enthusiastic believers in the use of subsurface conductors, could be cited, if further argument were necessary.

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* Proceedings A. I. E. E., vol. XXVIII., page 106.

Chapter II.

CABLE RECORDS

Operating Data. Reference to the records of breakdowns on high-tension cables in actual use, substantiates the claim to reliability for high-tension cables.

Mr. Peter Junkersfeld, referring to the Chicago system, says their cable troubles†

> "during the last three years have averaged only two cases per hundred miles per year. This includes all troubles on 9,000-volt cables from known or unknown causes, except those due to external injury to the lead sheaths."

In a more recent paper‡ Mr. Junkersfeld shows that during the preceding five and a half years, their 9,000 and 20,000-volt cables, aggregating 275 miles, had a total of only 48 breakdowns, of which 26 were due to external causes; or, ignoring damage from external causes, there was only one break-down per year per 15 miles of cable installed. Of the total number of burnouts, but a small percentage caused any serious shutdowns, and the company is now engaged in extending its underground system by adding 68 miles of 9,000-volt, 250,000-cm, three-conductor cable, and 44 miles of

† Proceedings A. I. E. E., vol. XXVI., page 1614. Part II.
‡ Proceedings A. I. E. E., vol. XXVII., page 1470.

additional 20,000-volt, No. 00, B. & S. three-conductor cable. The 9,000-volt cables are insulated with 6/32 inch paper about each conductor and a jacket or belt of 4/32 inch paper; the 20,000-volt cables with 9/32 inch paper around each conductor and a belt of 6/32 inch over all.

The Interborough Rapid Transit Company, after several years of operation, found it averaged only one breakdown per year per 62½ miles of cable, including the larger number of interruptions liable to incur on new installations.* Their Chief Engineer recently said:†

> "The number of burnouts per 100 miles of cable per annum, has fallen during the last two years to 0.28, or practically one fault per 400 miles of cable per year. That is a reassuring record; when our overhead transmission lines can show anything like it, we can look forward to reliable long-distance transmission."

The New York Edison Company has never had a complete shutdown of its system from any cause during the past 15 years, which, of course, includes its 200 miles of 6,600-volt system. Despite the difficulties encountered in making installations in the streets of New York and the early period at which much of its underground system has been installed, this company has had only 66 cable breakdowns of all kinds during the

* Proceedings A. I. E. E., vol. XXVI., page 1641. Part II.
† Proceedings A. I. E. E., vol. XXVIII., page 96.

nine years of high-tension operation. Of these breakdowns, 32 developed during operation and 34 were found either by periodic insulation tests or by inspections of the cables. Of the 32 that developed during operation, only 18 were caused by other than mechanical injuries, which, based on 200 miles, makes a record of one breakdown per year per 100 miles of cable operated.*

Mr. Charles E. Phelps, chief engineer of the Electrical Commission of the City of Baltimore, Md., shows that the breakdowns of all the various cables—including telephone, fire and police service—amounting in 1906 to nearly 300 miles, operating in Baltimore under various potentials and as high as 13,000 volts, were 148 for a period covering seven years; or, omitting the years 1903-4-5, when the breakdowns were abnormally high owing to street improvements consequent upon the fire and electrolytic action, there is an average of about one breakdown per year per 40 miles of cable of all kinds.

In Buffalo, where for years they operated 11,000-volt cables with commercial satisfaction and published records on two of their 9/32 rubber-insulated, three-conductor No. 000, B. & S. with no over-all jacket, lead-covered cables, each about 6 miles long show only two break-downs, these from mechanical injury, from 1900 to 1906.‡ The Public Service Corporation of New Jersey, has about 90 miles of underground and 65 miles

* Proceedings A. I. E. E., vol. XXVI., page 1615, Part II.
‡ Proceedings A. I. E. E., vol XXV., page 209.

of overhead cables operating at 13,200 volts, most of them being No. 00, B. & S. All these cables are three-conductor, paper-insulated 7/32 inch over each conductor, 7/32 inch over all with 1/8 inch lead sheath. The breakdowns from January 1, 1905, to October 1, 1908, 3.75 years, were, 11 in joints, 16 from external causes, 25 in cables, a total of 52. Thus the breakdowns, excluding external causes and defective installation, are 10 miles of cable per breakdown per year. Half the total number of cables had no trouble whatever; 5 cables had 1 each; 2 cables had 2 each; and 4 cables had 16 breakdowns, the latter being tie-lines not straight feeder-lines.

In a paper read before the Pittsburg Branch of the American Institute of Electrical Engineers, May 8, 1907, Mr. Charles W. Davis, reported figures relating to operating breakdowns on 1,462,000 feet of three-conductor lead-covered underground cable with potentials of from 11,000 to 16,000 volts installed on 14 different "construction jobs." The number of breakdowns of all kinds were 15, or one breakdown in joint for every 324 made; one breakdown in bends in manholes for every 340,000 feet of cable, and one breakdown for every 227,000 feet of cable lying wholly within ducts. Taking into consideration the four years covered by the breakdowns, there were from all causes whatsoever one breakdown per year per 390,000 feet (74 miles) of cable. Mr. Davis concludes his paper with the statement that the figures indicate that

> "practically all the defects or faults existing in a system will be weeded out by the initial high-voltage tests, the remaining few, if such still exist, being developed by the first few months of regular service. This conclusion is confirmed by observations on many other installations not covered by these remarks."

Among the examples of less extensive installations than those referred to above, may be mentioned the Twin City Rapid Transit Company, of Minneapolis, Minn., which has, at present, some 60 miles of three-conductor 13,000-volt, paper-insulated cable, much of which has been operating since 1897, and during the last three years it has had a total of only six breakdowns due to other than mechanical injury or poor workmanship. Two three-conductor cables, one with paper insulation and the other with rubber insulation, were installed in St. Paul, Minn., in 1890, for 25,000-volt service and have been giving satisfactory results under rather exacting conditions. Although the first underground installation made for operating potentials anything like as high as 25,000 volts, at a time when there was considerably less knowledge and experience with high-tension work, these St. Paul cables have a total record of but 37 failures from all causes in nearly eight years of continuous service, and 33 per cent of all the failures occurred in one year, due mainly to special difficulties. The cables are connected to the end of a 24-mile aerial

transmission line and are possibly therefore particularly subject to lightning.

At Montreal, Canada, four three-conductor cables are operated, each about 4,500 feet long, at 25,000 volts. These cables were installed in 1902, and during the six years intervening to date only eight breakdowns in all have been reported, although for part of their length they are installed in ducts under a canal.

There is a second installation under the St. Lawrence River at Montreal, of three-conductor and single-conductor rubber-insulated cables operating at 25,000 volts, part of which was made in 1906, and although connected to aerial lines and operating under water, only a total of one breakdown from all causes has been reported to date. The same company is also operating satisfactorily several 12,500-volt submarine cables.

Other Installations. At York Haven, Pa., in 1906, were installed two three-conductor rubber-insulated armored cables, each 3,280 feet in length, which have been operating continuously at 25,000 volts. These cables, between the generating station and one end of an aerial transmission line, are laid under water across the Susquehanna River. Philadelphia has about 100 miles of three-conductor lead-covered cables and Baltimore over 125 miles of No. 000 B. & S. three-conductor paper-insulated cables, all being operated at 13,200 volts under ground. In New Orleans, where the ducts are more or less continuously filled with water, there are about 8 miles, and in Boston and Washington, D. C., many miles of 6,600-volt cable. In Portland, Ore.,

an 11,000-volt submarine cable is in use. San Francisco, Cal., has been using 11,000-volt, three-conductor cable with "graded" insulation, about 10 years. In New York City, the passenger service of all railroads is operated entirely therein by electricity supplied at 11,000 volts through three-conductor lead-covered cables that are partly submarine and partly underground, or in iron pipes; in the Borough of Queens, another railroad system depends for the operation of a large part of its service upon 11,000-volt underground cables.

Under the Hudson River at Poughkeepsie, N. Y., there are two three-conductor rubber cables operating at 12,000 volts, and at Houghton, Mich., similar submarine cables are operated at the same voltage. Across Great Bay, at Portsmouth, N. H., there are two three-conductor rubber submarine cables, 5,000 feet in length, operating at 13,000 volts; and at Norfolk, Va., 4,000 feet of three-conductor submarine cable operating at 11,000 volts. Berlin is using three-conductor, steel taped 10,000-volt cables. In both Toronto and Quebec, Canada, and Providence, R. I., 12,000-volt underground cables are in use. Detroit, Michigan, is operating two No. 2, B. & S. three-conductor cables each 7.5 miles long, at a potential of 23,000 volts, and insulated with 2/32 inch rubber plus 6/32 inch varnished cambric about each conductor with a jacket of 3/32 inch cambric and a 3/32 inch lead sheath. In Rio Janeiro, Brazil, 13,000-volt cables have recently been installed, and about a year ago, there were put in operation in Durham and

Northumberland Counties, England, nearly 100 miles of 20,000-volt, three-conductor cable, with a considerable additional mileage of 12,000 and 6,000-volt cables, all of which, at last reports, were operating satisfactorily.

Spain has installed some cables operating at 15,000 volts, while in Italy they are using 10,000-volt cables at Naples, 12,000-volt cables at Genoa and 16,000-volt cables at Milan, and at the end of aerial lines some 20,000, 25,000 and even 30,000-volt underground cables.

The Moutiers-Lyons, France, continuous current, 60,000-volt transmission line feeds into two substations at Lyons, which are about 2½ miles apart, and connected in series through single-conductor underground cables. The cables have a section of 75 sq. m. m., and after being insulated, are protected with both a lead covering and steel armoring.

The above mentioned installations, although only a partial list, indicate, to some extent, the present-day wide use and exacting requirements made of high-tension cables. The successful employment of high-tension cables under water is particularly interesting, because of a popular belief that the use of high-tension cables under such conditions is almost impossible. Furthermore, such cables are often installed at the end or in the middle of a high-tension line, so that they are particularly subject to damage by lightning or the piling up of potential due to a change in the constants of the transmission line. Although the installations cited above refer only to constant potential circuits, it is

well known that there are miles of underground series arc circuits in most large American cities nightly carrying potentials of from 6,000 to 10,000 volts.

Exhibits. At the Louisiana Purchase Exposition at St. Louis, 1904, samples of cables designed for 50,000 volts (effective) and tested to 100,000 volts without perforation, were exhibited. Similar cables were shown at the Milan Exposition in 1906, which, being tested for breakdown point, in about 15-feet lengths, gave way at slightly above 200,000 volts.

The cable manufacturers in America and abroad are prepared to furnish what may fairly be termed high-tension cables. Some makers are prepared to supply and guarantee cable for 40,000 to 50,000-volt service, while one reliable manufacturer has submitted the writer a bona fide proposition for a client, to furnish single-conductor cables, lead-sheathed, for 75,000-volt service, pieces cut off to withstand a test of 150,000 volts, the price being comparable with that of a cable designed for more moderate voltages. One American manufacturer reports the production of a small amount of cable for commercial service, which satisfactorily withstood time tests of 150,000 volts and required about 240,000 volts to break down.

Cables in Use. Below is given a table showing some of the most interesting high-voltage underground and submarine cable installations in America, together with information as to the method of operating the character

and thickness of insulation, insulation per thousand volts, etc. It will be noted that the total thickness of insulation per thousand volts between conductors varies from over 4/64 inch in 6,600-volt cables down to about 1/64 inch in 25,000-volt cable. This difference is due to four different causes:

First. Difference in their value as dielectrics, of the materials employed as insulation.

Second. Ignorance as to the minimum insulation that is safe for a given potential.

Third. Difference of opinion among engineers as to the proper factor of safety to use in the design of high potential cables.

Fourth. The higher the operating voltage probably the less the proportionate increase in temporary potential strains due to surges, etc.; and hence, the less the necessity for a high factor of safety.

The list of 35 distinct installations hereafter given, aggregating over 2,300 miles of high-tension cable—operated under so many diverse circumstances as to voltage, current carrying capacity, character of insulation, outside metal protection, with widely varying electrical and climatic conditions—demonstrates that subsurface electrical transmission at high voltages cannot be considered in any sense experimental.

TABLE I.

LIST OF OPERATING THREE-CONDUCTOR, HIGH-TENSION, CABLE INSTALLATIONS.

NAME	Approximate Miles of Cables	Working Voltage	Neutral Grounded	Size of Conductor B. & S. or C. M.	Thickness of Lead Sheath in Sixty-Fourths of an Inch	Insulation	Thickness of Insulation: In sixty-fourths of an Inch: About each Conductor	Thickness of Insulation: In sixty-fourths of an Inch: Jacket	Thickness of Insulation: Per 1,000 Volts in thousandths of an Inch: Between Conductors	Thickness of Insulation: Per 1,000 Volts in thousandths of an Inch: To Ground
Brooklyn Edison Co., Brooklyn, N. Y.	130.	6,600	No	0000	8	Paper	11	11	52	52
Brooklyn Rapid Transit Co., Brooklyn, N. Y.	150.	6,600	No	250,000	8	Paper	13	10	61	54
Metropolitan Street Railway Co., New York, N. Y.	95.	6,600	No	0000	8	Rubber	12	12	57	57
		"	"	"	"	Paper	14	8	66	52
New York Edison Co., New York, N. Y.	200.	6,600	No	250,000	8	Rubber	12	12	57	57
						Paper	10	10	47	47
New Orleans Railway Co., New Orleans, La.	7.	6,600	No	0000	8	Rubber	10	10	47	47
		"	"	"	"	"	8	8	38	38
	1.	"	"	00	armored	"	"	"	"	"

Philadelphia Edison Co., Philadelphia, Pa.	55.	6,600	No	250,000	8	Paper	10	10	47	47
Third Avenue Railroad Co.,	70.	6,600	No	0000	8	Rubber	12	12	57	57
New York, N. Y.		"	"	"	"	Paper	10	10	47	47
Boston Edison Co.,	100.	6,900	No	0000	8	Paper	14	14	63	63
Boston, Mass.		11,000	"	6**	4	Rubber	14	none	20	20
Cataract Power & Conduit Co.,	28.	11,000	No	000	8	Rubber	18	none	51	25
Buffalo, N. Y.	45.	"	"	"	"	Paper	13	13	37	37
Hartford Electric Light Co.,	1.6	9,500	No	0000	8	Paper	12	12	39	39
Hartford, Conn.	1.4	11,000	"	00	"	"	"	"	34	34
	2.1	"	"	2	"	"	"	"	"	"
Hudson & Manhattan R. R. Co., New York, N. Y.	13.	11,000	Yes	0000	8	Paper	14	10	40	59
Interborough Rapid Transit Co.,	320.	11,000	Yes	000	9	Paper	14	14	40	69
New York, N. Y.	14.	"	"	0000	"	"	"	"	"	"
	24.	"	"	6	"	"	"	"	"	"
	1.	"	"	000	6 armored	Rubber	20	none	28	49
	.2	"	"	6	"	"	"	"	"	"
Long Island Railroad Co., Long Island, N. Y.	27.	11,000	Yes	250,000	9	Paper / Cambric	14	14 / 1	40	71
N. Y. Central & Hudson River	1.5	11,000	Yes	0000	armored	Rubber	13	13	37	64
R. R. Co., New York, N. Y.	90.	"	"	"	9	Paper	14	12	40	64
		"	"	"	"	"	14	14	40	68
		"	"	"	"	Cambric	12	12	34	59
Norfolk & Portsmouth Traction Co., Norfolk, Va.	2.4	11,000	No	00	armored	Rubber	12	12	34	34

**Single-Conductor.

TABLE I.

LIST OF OPERATING THREE-CONDUCTOR, HIGH-TENSION, CABLE INSTALLATIONS.

NAME	Approximate Miles of Cables	Working Voltage	Neutral Grounded	Size of Conductor B. & S. or C. M.	Thickness of Lead Sheath in Sixty-Fourths of an Inch	Insulation	Thickness of Insulation: In sixty-fourths of an Inch: About each Conductor	Thickness of Insulation: In sixty-fourths of an Inch: Jacket	Thickness of Insulation: Per 1,000 Volts in thousandths of an Inch: Between Conductors	Thickness of Insulation: Per 1,000 Volts in thousandths of an Inch: To Ground
Pacific Gas and Electric Co., San Francisco, Cal.	15.	11,000	No	2	8	Rubber*	12		34	
						Paper		6		26
	10.	"	"	"	"	"	10	10	28	28
Rochester Railway & Light Co.,	11.	11,000	Yes	1	8	Paper	12	12	34	59
Rochester, N. Y.		"	"	00	"	"	14	14	40	68
		"	"	250,000	"	"	"	"	"	"
Houghton County Electric Light Co., Houghton, Mich.	.8	12,000	No	4**	armored	Rubber	12	none	31	31
Ontario Power Co., of Niagara	.4	12,000	Yes	250,000	7 armored	Paper*	12	12	31	54
Falls, N. Y.	.5	"	"	"	8 armored	Paper*	14	10	36	"
	.1	"	"	6	8 armored	Paper	"	"	"	"
	.3	"	"	500,000**	7	Cambric	20	none	26	26
Poughkeepsie Light, Heat & Power Co., Poughkeepsie, N. Y.	.6	12,000	No	2	armored	Rubber	12	10	31	28

Quebec Canadian Electric Co., Quebec Canada.	1.2	12,500	No	3	armored	Rubber	16	none	40	20
Narragansett Electric Light Co., Providence, R. I.	2.	12,500	No	0	8	Rubber	18	none	45	45
Rockingham County Light & Power Co., Portsmouth, N. H.	1.4	13,000	No	6	armored	Rubber	13	10	31	28
Twin City Rapid Transit Co., Minneapolis, Minn.	60.	13,000	Yes	3	8 armored	Paper	12	12	29	50
		"	"	0	8	"	"	"	"	"
		"	"	0000	"	"	"	"	"	"
		"	"	"	8 armored	"	"	"	"	"
Consolidated Gas, Electric Light & Power Co., Baltimore, Md.	25.	13,200	Yes	0	8	Paper	14	14	33	57
Milwaukee Electric Railway & Light Co., Milwaukee, Wis.	1.	13,200	Yes	0	10 arm'd	Rub'r* Paper	16	12	38	57
		"	"	"	10 arm'd	Rub'r* Paper	14	14	33	"
	27.	13.200	"	0	10	Paper	16	12	38	"
	.6	"	"	"	10	Rubber	16	12	"	"
Philadelphia Rapid Transit Co., Philadelphia, Pa.	100.	13,200	No	00	10	Paper	12	12	28	28
		"	"	000		"	"	"	"	"
		"	"	0000		"	"	"	"	"
Public Service Co. of New Jersey, Newark, N. J.	90.	13,200	No	00	8	Paper	14	14	33	33
		"	"	1	"	"	"	"	"	"
		"	"	4	"	"	"	"	"	"
United Railways & Electric Co., Baltimore, Md.	125.	13,200	Yes	000	8	Paper	14	10	33	49
		"	"	"	10	"	"	14	"	57
		"	"	0000	"	"	"	"	"	"

*Graded Insulation.

TABLE I.

LIST OF OPERATING THREE-CONDUCTOR, HIGH-TENSION, CABLE INSTALLATIONS.

NAME	Approximate Miles of Cables	Working Voltage	Neutral Grounded	Size of Conductor B. & S. or C. M.	Thickness of Lead Sheath in Sixty-Fourths of an Inch	Insulation	Thickness of Insulation: In sixty-fourths of an Inch: About each Conductor	Thickness of Insulation: In sixty-fourths of an Inch: Jacket	Thickness of Insulation: Per 1,000 Volts in thousandths of an Inch: Between Conductors	Thickness of Insulation: Per 1,000 Volts in thousandths of an Inch: To Ground
Commonwealth Edison Co.,	340.	9,000	Yes	0000	8	Paper	12	8	42	60
Chicago, Ill.	55.	20,000	"	00	"	"	18	12	28	41
Edison Illuminating Co.,	15.	23,000	Yes	2	6	Rubber	4			
Detroit Mich.						Cambric	12	6	22	26
York Haven Water & Power Co., York Haven, Pa.	1.3	24,000	No	00	armored	Rubber	16	14	21	19
St. Paul Gas Light Co.,	3.	25,000	No	2	8	Rubber	14	10	17	15
St. Paul, Minn.	3.	25,000	"	"	"	Paper	18	8	22	16
Montreal Light, Heat & Power Co., Montreal Canada.	3.4	25,000	Yes	0000	6	Paper	20	12	25	35
Shawinigan Water & Power Co.,	5.	25,000	No	00**	armored	Rubber	28	none	17	17
Montreal, Canada.	1.2	"	Yes	1	"	"	16	16	20	35
	1	12,500	No	3	8 armored	"	12	12	30	20

**Single-Conductor.

Chapter III.

ADVANTAGES OF UNDERGROUND CABLES.

Existing Conditions. In American cities and towns of any considerable size the local regulations usually require that all wires be put under ground, except in the more sparsely populated portions. Where such requirements exist, the distribution of electrical energy is at present being generally done by means of lead-covered cables threaded through vitrified clay, wood fiber or bituminized paper ducts laid in Portland cement. By far the greater proportion of work installed under the conditions cited is for low-potential distribution, although in the larger cities and as a section of a transmission line entering such a city district or passing under a river, many high-tension underground installations can be shown. The relative advantages of high-tension underground, as against aerial constructions, cannot perhaps be properly considered in such connection, because subsurface construction is more or less compulsory. It has, moreover, rather been the practice of engineers not to resort to the use of high-tension underground installations except under some such compulsory conditions. As the advantages and reliability of high-tension cable construction are realized, a wider use of such cables is sure to result.

Among the advantages are:

First, Lightning. Absolute freedom from interruption of service and damage to apparatus from lightning disturbances. It is generally recognized and acknowledged that any system of electrical distribution which is completely underground is immune from atmospheric lightning, although, of course, disturbances and undue potentials that arise by reason of surges, arcing grounds, etc., may occur with underground as with aerial systems.

Second, Breakdowns. Less liability of interruption of service from breakdowns.

> "In New York where probably there is more cable than any other city in the United States, or in the world, interruptions of service due to the breaking down of a cable are almost unheard of."*

Most of the breakdowns occurring in high-tension cables are the result of "human frailty," which can be largely anticipated and avoided.

> "As a rule, more trouble will develop on underground cables due to poor work on installation rather than to faults in the cables themselves."†

Engineering opinion is practically unanimous in the statement that the weakest point of cable installation

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* C. W. Rice, Proceedings A. I. E. E., vol. XXIV., page 416.

† I. A. Ferguson "Underground Electrical Construction", Proceedings International Electrical Congress of St. Louis, 1904.

is the joint. It is essential that the insulation at the joint shall exclude air and moisture, and be as solid and perfect as the balance of the insulation. To indicate the perfection of workmanship and material which may be attained by due care, it is said with regard to the method of making cable joints employed by the Commonwealth Edison Company, of Chicago, that*

> "the method (see page 70) has been tried for six years on an installation comprising 420 miles of high-tension cables. (This figure includes 4400-volt circuits. Ed.) During the entire term of this test only one failure of a cable joint occurred on these lines, and this was plainly attributable to external causes."

Surprising as it may seem at first thought, experience shows that the short-circuiting or grounding of a high-tension cable results in as little as or less damage than in the case of low voltage cables. With low voltages and large currents, the burning resulting may be serious, and in at least one instance brought to the author's attention, damaged several miles of cable; whereas, with high voltages, the arc is so severe as to promptly extinguish itself or open the station safety devices without burning more than perhaps two to five feet of cable.

On account of the increased cost of cables with high factors of safety, there is a strong tendency to reduce the thickness of insulation and thereby the cost, but at

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* Electrical World, page 544, Sept. 5, 1908.

an increased risk of breakdowns. This is being counteracted by some manufacturing companies through the adoption of the same business methods of installing high-tension underground cables that were employed and still are, to some extent, used in connection with the installation of storage batteries, namely, furnishing, drawing in and connecting up the cables complete, then undertaking to maintain them, as against defects in manufacture or installation, for an annual charge, which in some cases, is as low as one-half of one per cent of the total cost of the cables.

Third, Interference. Fewer interruptions of service from extraneous interference. Short circuits and grounds are more or less continually occurring with aerial lines due to breaking of mechanically weak wires or insulators, storms of wind and ice, objects falling across the wires and short-circuiting them, and malicious interference. With underground conductors, annoyances of the above character are almost entirely done away with, the cables usually being installed in ducts of tough material, enclosed in concrete several inches thick, the whole being from one and a half feet to three feet below the surface of the ground, except at manholes, which are protected by double, heavy iron covers, affording protection against almost anything but dynamite. In case of strikes, it would be much easier to patrol and protect lines in conduits than those carried on poles, because the latter can be damaged from a distance by rifle shots or wires thrown

over the lines, whereas underground construction must be directly approached before it can be injured.

> "In the overhead system (Boston), the troubles are ten to one in comparison with the underground cable system, almost all of these occuring in cable newly installed."*

Operators of aerial circuits usually do not keep as full and complete records of interferences caused by failures of their lines as do those in charge of cable installations. Lack of explicit information frequently leads those operating overhead lines to the conclusion that their interruptions are not anything like as frequent as are troubles in cable circuits, indicated by records that have been published. The following record for the last twelve months furnished by a company maintaining detailed accounts of each shutdown of their aerial line may be taken as indicating results at least as favorable as the average, because the line is located too far south to be ever troubled by snow or ice, is well built and operated under independent, progressive management. The line is a little over 100 miles long and shows one breakdown per year for each 6 miles of line.

It must be admitted that a breakdown in a cable is more serious than in an aerial line, because the latter can be repaired more quickly and with cheaper labor than the former; but breakdowns in cable systems are

* Proceedings A. I. E. E., Jan., 1909, page 14.

not near as frequent as interruptions of service with aerial lines, despite the fact that many high-tension cables are operating with rather light insulation for the service.

Fourth, Accidents. The liability of accident to the public with consequent damage suits is almost entirely removed. The only likelihood of danger is from explosions of gas that may accumulate in ducts or manholes, but with proper design and construction this danger can be practically eliminated. Frequent injury or death to individuals coming in contact with broken aerial conductors are too much of an every-day occurrence to need any argument to prove the desirability of underground construction from the standpoint of safety to the public, regardless of aesthetic considerations or the inconvenience of poles in streets.

The danger to employees is less with underground than aerial construction for the reason that in repairing or stringing new aerial lines there are usually other live circuits on the same pole with which the workmen may come in contact, whereas with underground construction, the live cables are enclosed in lead sheaths which are grounded, and therefore, harmless.

Fifth, Interruptions. With aerial circuits, interruptions in the continuity of the transmission system usually occur without any forewarning. In contra-distinction to this the weakening of the insulation of cables is often determined by tests or by suitably designed indicating instruments, sufficiently in advance of

the actual breaking down of the insulation to allow transferring to another cable without interruption of the service. There has been developed by Messrs. Torchio and Varley, of New York, a device now in commercial use which takes into account the unbalancing of the condenser capacity current, when the insulation of a conductor begins to depreciate, and gives warning of approaching danger sufficiently in advance of a breakdown to allow the cable to be disconnected.

Comparative Example. As illustrative of the relative cost of aerial and underground constructions, the following figures are given, having been prepared in connection with plans for an actual installation of underground cables for the transmission of 20,000 H. P., 15 miles across country, from a certain hydro-electric station to a substation in a neighboring city. By the use of conduits laid in the highways, the cost of expensive rights-of-way, real estate, building and lowering transformers for a substation at the outskirts of the city and liability of interference with the circuits will be avoided. While the increased cost of the underground construction seems large compared with aerial lines, the difference will be only a small percntage of the total cost of the complete system, as noted in the following table:

COMPARATIVE COSTS OF SYSTEMS.

AERIAL LINES.

Private right of way across country.........	$45,000
Steel towers with three circuits, complete for 15 miles, ...	85,000

Three miles of 8-duct conduit, at $7,000 per mile, ...	21,000
Six 10,000-volt paper cables (1 spare), at $1.10 per ft., ...	105,000
Substation complete, with 18,000-kw transformer capacity	95,000
	$351,000

UNDERGROUND LINES.

Eighteen miles of 4-duct conduit, at $5,000 a mile, ...	$90,000
Three 25,000-volt paper cables (1 spare), at $1.50 per foot, ...	428,000
	$518,000

The above example illustrates, of course, only one set of conditions. The use of cables designed for other voltages than those specified would naturally result in different total costs. Again, when considering the cost of transmission lines in connection with station apparatus, it might be found advisable to generate at 15,000 volts and transmit at that voltage, thereby avoiding the cost of step-up transformers, included in the estimates based on 25,000 volts for transmission. The principle point to be brought out by the figures is that the use of high-tension underground cables is not limited to city streets; but, under certain circumstances, may be advantageously used across country.

Chapter IV.

CABLE INSULATION.

Dielectrics Employed. While it should not be the duty of the purchaser to attempt to specify the details of insulation manufacture and application any more than he attempts to specify all the details of construction of standard apparatus used in the electrical business, nevertheless, in the present state of the art it seems necessary that the engineer be well informed as to properties and limits of cable dielectrics and their methods of production and application so as to be able to control the manufacturer, unless the latter is willing to assume all responsibility for his product, backing that up with a guarantee covering a long period of years.

The early attempts in America at operating conductors underground, were made in the larger cities by the Edison Companies. The original system consisted of iron pipe, usually in 20 feet lengths, containing copper rods covered with a light cotton or jute insulation embedded in bituminous compounds. The pipes were called tubes, and contained two conductors for feeders and three conductors for the three-wire mains; the conductors were united at their ends by means of flexible conductors enclosed in cast iron couplings or junction boxes filled with compound similar to the tubes.

Even for the low potentials employed by the Edison Companies, the type of insulation available, with the low melting point of the compound, was soon found insufficient and unsatisfactory for subsurface work and resulted in the adoption of rubber and gutta percha for underground insulation.

The lack of flexibility and accessibility in a system where the conductors could only be examined or withdrawn by tearing up the streets, developed nearly 25 year ago, the drawing-in system, namely, the use of ducts united by manholes permitting the drawing in of a thoroughly insulated, usually lead-covered, flexible conductor. Although the duct system has become almost universally accepted and adopted in America, the solid system is still being used with satisfactory results abroad, and for lower voltages and special installations may, in many cases, be desirable. Recent improvements in the quality of the insulating and water-proofing compounds with reductions in their price, may yet see the more extended use in America of the solid system, which permits the installation of a bare conductor in situ.

As increasingly higher potentials were attempted, history shows that rubber and its compounds were almost exclusively used for insulation; however, on account of its high cost substitutes were quickly sought and paper carefully applied and properly treated was soon found to be satisfactory, provided dampness and moisture could be kept away. This was accomplished by inclosing the insulation in a lead sheath, which, as long

as it remains intact, allows paper insulated cables to give very satisfactory service for the highest voltages yet commercially employed under ground. More recently, shellaced cambric has been used, which, although more costly than paper is less expensive than rubber, and unlike the former does not quickly depreciate in the presence of water. The latest development is "graded" insulation, which is a combination of different dielectrics or the use of a nonuniform material.

Rubber Insulation. Rubber, the unique vegetable product, for which no full substitute has ever been found, makes an unsurpassed dielectric when properly treated, by reason of its insulating qualities, extreme flexibility and imperviousness to moisture. Crude rubber varies widely in its characteristics and value, depending on its age, purity, and to some extent, the locality in which it is produced. It comes on the market mixed mainly with impurities such as bark, clay and other foreign substances which are removed by washing and manipulation, resulting in a reduction in weight of from 10 to 50 per cent, the finest Para rubber losing about 18 per cent.

Rubber used as insulation is adulterated or degraded with various substances, so that the compound contains at most, only 40 per cent of pure rubber, more usually about 30 per cent in the highest grade insulation down to 5 or 10 per cent in the poorer rubber-covered wires, with no rubber in some cheap insulations which are called rubber.

Pure rubber is valueless for insulating purposes, being too soft, hydroscopic, and readily oxidizable. When proper foreign substances to the extent of about 60 per cent or more, including about 3 per cent of sulphur, are added and the compound vulcanized by heating to from 250 to 300 degrees Fahr., the rubber is made stable, tough and durable, its value as a dielectric depending upon the details of this treatment. The exact temperature and duration of time necessary for vulcanizing depends on the grade of rubber, the ingredients used, and the percentage of sulphur added to the compound. The adulterants most commonly used for making the better grade rubber compounds are dry mineral matter or reclaimed rubber; the composition of the particular material used for compounding, may, in many cases, be left to the discretion of the manufacturer. Proper vulcanization is as important in producing high grade insulation as the quality of the rubber used or the method of compounding. The amount of free sulphur left in the compound changes with oxidization. In no case should the free sulphur exceed about 1 per cent—the amount being determinable from the acetone extract—as an excess shortens the life of the rubber. Sulphur gives an indication of the quality of the rubber used, because much sulphur is required to vulcanize poor rubber and a large amount of combined sulphur may be taken as an indication that it was required in order to produce vulcanization.

The best rubber comes from South America, and is known as Para. Weber states that the reason for the

inferiority of the African rubber is generally due to the presence of albuminous substances which are not removed by washing and which result in a brittle insulation; he also states that light will oxidize rubber, the more rapidly the less the degree of vulcanization. While a compound containing 30 to 35 per cent "old up-river" Para rubber is generally accepted as the requirement for insulation to be used in high-tension work; as a matter of fact, it is almost impossible for any chemist to ascertain, after vulcanization, just what the constituents of the insulation may be, and while any number of tests have been proposed, it is much better to rely on the standing and integrity of the manufacturer and his guarantees than to do business with unreliable firms, expecting to prove from an examination of the product furnished whether or not they are fulfilling contract specifications. While 30 per cent Para seems to insure high grade insulation, it is beyond controversy that certain compounds containing less than 30 per cent Para give most satisfactory results in service, although they fail to meet some of the tests hereafter indicated, as the requirements for the best insulation.

High-grade rubber is not only very elastic but possesses great tensile strength. If over vulcanized it will break; if under vulcanized it is not elastic, so that strength and elasticity are fair indications of its value as an insulating material. Those best informed agree that a new sample of 30 to 35 per cent Para compound properly vulcanized, should be capable of withstanding

a tension of 700 to 800 pounds per square inch before breaking, and when stretched from two to three times its original length should return to within at least 125 per cent of its original length, when at a temperature of about 100 degrees Fahr. Although insulation containing appreciably less than 30 per cent of Para, with additional amounts of cheaper rubber, making a total of say, 40 to 50 per cent, may pass the tensile and elastic tests mentioned above, such test usually indicates that the insulation contains only rubber, and no shoddy or bituminous products; but some authorities claim that a compound containing only Para will have considerably greater resistance to puncture than insulations containing the same proportion of Para with a proportion of inferior rubber in the materials used in compounding.

For the larger proportion of cables manufactured, namely, those used for low tension work, say under 5,000 volts, 30 per cent pure Para is unnecessary, the cheaper grades, as high grade Ceylon, Malay or African Lapori, for example, giving very satisfactory results for this particular class of low-voltage work, while even the rubber produced from the Mexican guayule is used for the insulation of telephone wires.

The quality and life of rubber insulation has heretofore generally been considered as indicated by the amount of resinous or extractive matter it contained. A high percentage of resinous matter, say 15 to 20 per cent, was taken to indicate a cheaper and poorer

grade of rubber, whereas a low percentage, 1 to 2 per cent, was assumed to be found only in the best grade of Para, which come from South America.

Owing to some unknown cause, the amount of extractive matter increases largely in the working and mastication of the gum, there being still further increase during vulcanization. The amount of resinous matter is determined by digesting the gum in acetone, which dissolves out the extractive matter. Standard practice specifies that the acetone extraction shall be carried on for five hours in a Soxhlet Extractor, as improved by Dr. C. O. Weber. It is important that care be taken in making the tests, not only that proper conditions should be observed, but that the duration of the test is as specified, otherwise the results may vary widely. As an example of this, it may be stated that in a given instance, a 40 per cent Para rubber compound, such as used by the United States Government, if heated for a period of about twelve hours, to 105 degrees Cent., in a drying oven prior to being treated with acetone, resulted in increasing the weight of the acetone extract from 2 per cent to 8¼ per cent. The greater part of this increase took place during the first few hours of heating. In the same way, the longer an acetone test is continued the larger the percentage of extract obtained, although by far the greater proportion is given off during the first five hours. From the above, the necessity of properly conducting and carefully timing the length of the test will be recognized. The rubber

to be tested should first be dried over calcium chloride in a vacuum at slightly elevated temperature, and then treated with acetone in the extractor.

It should be understood that the acetone test determines the quality of the rubber compound, so that the usual maximum precentage limit of 5 per cent, for example, must be raised provided it is intended that the manufacturer shall be permitted to introduce other substances in the adulterant used for compounding, which in themselves contain extractive matter. If it is clearly stated in the specifications that only Para rubber, to a definite percentage is to be used and that the remainder of the compound is to be of some other material than rubber, then the 5 per cent should not be exceeded.

There exists a wide difference of opinion and practice as to the proper limit of extractive matter that should be permitted in a high-grade compound. Some specifications* specify that the acetone extract should not exceed 3½ per cent by weight, of the gum in the compound, while the more usual specification and that issued by the rubber manufacturers, sets the upper limit of extractive matter, as 5 per cent by weight, of the total compound, that is, in a 30 per cent Para compound, the weight of extractive matter shall not exceed about 17 per cent of the weight of the gum. More recent experience and research has shown that some African rubber gum may contain as

* Specifications of the Railway Signal Association.

low as 2 to 3 per cent of extractive matter, while some high-grade Para, giving excellent results in service, will contain over 4 per cent of such matter. With these wide variations and with the knowledge that by proper treatment the amount of acetone in a compound can be reduced to even 2 or 3 per cent if necessary, the value of the acetone test is being discredited and abandoned by many engineers; for example, the Specifications for Electric Wires and Cables, issued by the Navy Department,* omit all acetone tests whatever, depending upon other tests entirely to determine the value of the compound.

The introduction into rubber compounds of waxy ingredients such as paraffine, for the purpose of increasing megohm measurements, etc., should be limited; a small amount, say 3 to 4 per cent of the weight of the rubber gum will not prove injurious.

In America the rubber compound is applied to a conductor in either of two ways:

(a) By passing the conductor through a press similar to a lead machine and applying the compound in a plastic state at relatively high temperature as a seamless tube, as the conductor passes out of the machine. This is called "spewing," and is used more particularly with smaller sized conductors.

(b) By applying the insulation in a longitudinal strip by means of a machine which folds the compound

* Dated June 10, 1908.

around the conductor and unites the edges in a continuous and almost invisible seam. As judged from practical results, the strip insulation seems about as satisfactory and reliable as the seamless insulation, and it has the further advantage of keeping the conductor properly centered and having imperfections in one layer covered by additional layers.

In Europe the insulation of conductors by winding with rubber tape has been successfully accomplished. This method should be expected to result in a more uniform dielectric capable of withstanding greater potential stress, for a given thickness, than when applied by "spewing" or in strips.

With any method of applying the compound, a braid or tape over all, is employed to better hold the compound in position and prevent its swelling and becoming porous during vulcanization; such tape has no particular value as a dielectric.

Rubber insulated underground cables are usually covered with a lead sheath both for mechanical protection and to guard against attacks from oils, acids or oxidization. The substitution of a fibrous covering served with a bituminous compound or something of that sort, has been attempted in place of the lead sheath and is said to be found satisfactory under some conditions, particularly where electrolysis cannot be avoided, although such substitution is ordinarily based primarily on considerations of cost.

When completed the rubber insulated cable is the most flexible of all, and should be capable of being

bent on a radius equal to five times its diameter, bent similarly in a reverse direction; have the process repeated three times and then withstand puncture and ohmic tests hereinafter specified.

Paper Insulation. Paper insulation is made by taping paper ribbon about a conductor in successive layers until the required thickness is obtained. The cable is then dessicated by baking, or more satisfactorily by giving it a preliminary drying in air and placing in a vacuum, and immediately immersed in a bath of oily insulating resinous compound, at a temperature of not less than 120 degrees Cent. (250 degrees Fahr.), until thoroughly saturated; the whole is then promptly enclosed with a lead sheath, which is necessary to exclude moisture, and at the same time, holds the insulating compound in position. The value of the insulation as a dielectric depends on the quality of the paper and the compound.

The best paper is that made from Manilla fibre, primarily because of its mechanical strength. The paper should show uniform texture when held to the light, be free from coarse or metallic particles, or pin holes, and should show no trace of chlorine or other residual chemicals, or be loaded with low grade material. Strips of paper five-thousandths of an inch in thickness, and one inch wide, after being impregnated with the insulating compound to be used, should sustain without breaking, a load of 40 pounds. The thickness of paper ordinarily used is from five to six-thousandths of an

inch, with a tendency toward thinner papers for the higher voltages. The width of the paper ribbon employed varies from one to two and a half inches, the widest ribbon being used on the conductors of large diameter.

Rosin oil, which is the diluent and chief ingredient of the fluids used for impregnating paper insulation, is obtained from the distillation of rosin gum. Rosin comes from oleo turpentine, which is exuded by the long-leaf pine or coniferous trees. Rosin produces rosin oil and pitch; the former is distilled a second time producing what is known as "second oil," which, more or less treated or refined, is the impregnating fluid used as the principal dielectric in paper-insulated cables. The method of preparing the rosin oil for impregnating, varies with the different manufacturers in accordance with their particular formulae—which like those relating to the ingredients of rubber compounds, are guarded as "State Secrets"—and make the chief difference in the quality of paper insulation.

Lack of uniformity in commercial rosin oil, its liability to contain moisture and deleterious substances, necessitate the greatest care in the proper preparation of rosin oil for insulating purposes. A. Bartoli* gives the relative value of insulating oils, and it is noteworthy that those which are the more capable of being oxidized are the less valuable as dielectrics, which would indicate a departure from the present use of rosin oil in its usual unoxidized condition.

* L. L. Nuovocimento, 1890, vol. XXVIII. page 25.

In the application of rosin oil to paper, the oil —abietic anhydride, $C_{44}\ H_{62}\ O_4$,—seems to soak into the paper leaving the rosin largely on the outside. The insulation shows the highest puncture tests when the pores of the paper are filled with oil, which may take many hours or even days, at low temperature, to accomplish, where the impregnation is made through many layers of paper.

The use of too viscuous oil results in the absorption of the diluent by the paper leaving the rosin "high and dry," resulting in a non-flexible and hard cable. Recently, the advantage of using a more fluid oil has been recognized, which, while reducing the megohm measurements, results in a cable that will withstand satisfactorily high puncture tests, and at the same time, make it more flexible and thus largely avoid the difficulties that have heretofore been encountered in handling paper cables, namely, their liability to split or crack when bent, particularly in cold weather. Investigation and experiment has recently produced a very much improved quality of rosin oil, which does not become viscous even at zero degrees Fahrenheit, so that one very practicable objection to paper cables, their lack of flexibility, is now likely to be removed. With all cables, however, it is just as well to keep them in a warm room for some hours if they are to be installed when the temperature is below freezing.

As long as the paper insulation of cables can be kept intact within their lead sheaths, they are found to give most excellent satisfaction; but if by reason of

defects in manufacture, electrolysis or damage, the sheaths are punctured so that water, or even water vapor, can gain access to the dielectric, the breaking down of the insulation is a question of minutes, or at most, hours.

At the time of manufacture, the lead sheathing of paper cables is continued so as to completely enclose and protect the ends of the insulated conductors with lead, to keep out moisture. The lead sheath should never be stripped off the ends of the cable until everything is prepared for making a prompt and dry joint, or inserting in an "end bell" for making a terminal. The stiffness of paper cables is related to their temperature and the quality of the impregnating fluid; but with the use of the best oils, a cable should be capable of being bent back and forth three times, on a radius of eight times its diameter, even at a temperature of freezing, and then withstand the regular puncture and ohmic tests.

On account of their relatively low first cost, paper insulated cables are being more and more used for all services—even submarine—and are proving successful, despite their inherent limitations. There are more miles of high tension cables in use insulated with paper than with all other insulations combined.

Cambric Insulation. A recently developed dielectric for insulating high-tension cables is varnished muslin or cotton fabric usually called cambric. The muslin is coated on both sides with several separate films of insu-

lating varnish, or in some cases, linseed oil compounded with some paraffine or ozokerite, or even rosin. The coated material is then cut into strips making ribbon which is wound spirally about the conductor in layers to any desired thickness; between the wrappings is applied a thin layer of viscuous adhesive compound which prevents the unwrapping of the tape when cut, largely precludes the absorption of moisture, and increases the flexibility by permitting the layers of cambric to slide upon one another. More usually a thin layer of pure rubber, or in some cases, treated paper or cloth, is first applied to the conductor before the cambric insulation is put on, in order to prevent the varnish from attacking the copper, and in the case of the rubber, to secure a dielectric or high resistance next the conductor. Asbestos has also been used as a separator, with the idea, among others, of permitting greater heating, that is, greater carrying capacity, without injury to the varnished cambric.

The application of the dielectric by taping, with the use of a filling compound, as is the case with paper insulation, should result in avoiding such defects in the dielectric as the formation of air pockets and decentralization of the conductor, that are possible with "spewed" rubber insulation. The splicing of cambric cables is more simple than with paper insulation, as moisture is not as readily absorbed nor is the cambric attacked by mineral oils, making it particularly convenient for connecting into apparatus submerged in oil, as switches, transformers, etc. For station wiring,

varnished cambric can be installed without a metallic sheath and does not require end bells, for which service it is usually finished with a tape and asbestos braid.

Cambric insulated high-tension cables should not be continuously operated at higher temperatures than rubber, preferably not above about 65 degrees Cent., whereas paper insulated high-tension cables may be safely operated at about 80 degrees Cent. Aside from somewhat increased flexibility and less liability of injury from moisture in case of injury to the lead sheath, or where it is desired to install cables without a lead sheath, as in a power station, cambric insulation seems to offer no very especial advantages over paper insulation, particularly at existing prices, as the paper cables are appreciably less expensive than those with cambric insulation. The usual practical advantage advanced for cambric insulation, as against rubber, seems to be that of cost; but, on the other hand, charring between the layers of the cambric has been observed, due possibly to air bubbles; and the question has also been raised whether the ageing and drying out of the varnish will not cause the insulation to become friable and deteriorate, particularly if operated at relatively high temperatures.

Shellaced cambric insulation is considerably more pliable than paper and the cable complete should withstand the puncture tests given on a later page after being bent three times in opposite directions on a radius equal to six times its diameter.

Dielectric Stresses. The dielectric strength of rubber is much higher than that of treated paper or varnished cambric, being as a maximum as high as 20,000 volts per millimeter of thickness in thin sheets, whereas the same thickness of treated paper will not withstand more than from one-half to two-thirds this potential, so that unless some other materials are found, or further improvement be made in paper insulation, which seems possible, it is likely that rubber must be used, at least in part, on cables designed for the highest potentials, in order that the completed cable may not become so great in diameter as to be cumbersome and impracticable to handle. It was early appreciated that doubling or tripling the thickness of a given insulation did not increase its ability to stand up under applied electrical stresses, in anything like the same ratio. It was found, with an insulation of homogeneous material, that the fall of potential through the insulation, from the conductor to the lead sheath, was not uniform but increased very much more rapidly nearest the conductor, being for a certain insulation, for example, 5,000 volts per millimeter of insulation next the conductor and only 1,000 volts for the same thickness next the sheath. Without more fully considering what may be the fall of potential along the radii, from the surface of the conductor to the sheath, or the complex formulae by which these values may be calculated, for various dielectrics, it may be said that both theory and experiment prove the fact; and, furthermore, that the rate of fall of potential varies with different materials,

depending upon their various specific inductive capacities. Knowledge of these conditions led an Englishman, Mr. M. O'Gorman, and an Italian, Mr. E. Jona, about the same time, to suggest equalizing the fall of potential so as to secure a uniform or practically uniform "potential gradient" throughout the insulation either by impregnating the insulating material to different extents depending on its distance from the conductor, or by applying successive layers of insulation each made up to have different inductive capacities with the layers arranged so that those of material with the highest capacity should be nearest the conductor. This arrangement of insulating material causes the outer layers to support approximately the same strains per unit of thickness as the inside layers; and hence, the total stress due to the potential of the conductor is supported by a wall having a total thickness of insulation very much less than if homogeneous. Theoretically, the insulating material should vary gradually instead of by layers; but this, of course, is impracticable, so that the fall of potential from conductor to sheath proceeds by a series of small steps instead of in a smooth curve.

Experiment with high potentials seems to have demonstrated that the distribution of stress in solid dielectrics, such as paper or rubber, is very similar to that which we know occurs in air. About conductors of small diameter air apparently breaks down, resulting in a conducting medium made up of the solid conductor and air, which is considerably larger in diameter than

the solid material. It is probable that similar action takes place with the insulation about conductors of small diameter, so that the dielectric itself, for a small distance from the conductor, breaks down and becomes also a conducting medium. In any case, it is clear that insulation of a given character about a conductor of large diameter will sustain a considerably higher potential before puncture, than the same insulation about a small conductor. As a result of experiments made by him, Mr. Jona concludes that by sheathing a copper conductor in lead, thus both increasing its diameter and affording an absolutely smooth and cylindrical exterior, there may be produced "a diminution in the potential gradient in the very first stratum of dielectric of something like 20 to 30 per cent or even more," and he has so sheathed with lead high-tension cables made under his direction.

Graded Insulation. The theory of applying layers of insulating material having different capacities has been carried out in practice and the value of "graded" cables for high potentials successfully demonstrated. For example, there was shown at the 1906 Milan Exhibition, such cable, having a total thickness of insulation of only 14.5 m.m., though designed for a normal working pressure of 100,000 volts, and at present, there are installed across the Lake of Garda, Italy, single-conductor "graded" cables operating at 13,000 volts. These cables are insulated by several layers of vulcanized india rubber to a total thickness of 5.5 mm. Outside the rubber is a coating of 1.2 mm. of gutta percha

to further insure imperviousness. This is covered with "tanned jute" and armored with No. 18 steel wire 3 m.m. in diameter. As three of these cables are required for three-phase operation an interesting plan was adopted in order to avoid undue self-induction; each of the steel wires used in armoring was wrapt with tarred hemp before being wound around the insulated conductor. The result of this experiment seems to be satisfactory, as the drop of pressure due to self-induction is reported to have been reduced to the same amount as the drop due to the ohmic resistance. Connecting the generating station and transformer house of the Ontario Power Company at Niagara Falls, are some high voltage "graded" cables.

Variation in the capacity of rubber used for "graded" cable is obtained by "loading" it with other substances such as talc, zinc, etc., while the capacity of paper may be similarly varied by changing the quality of the paper or the process of impregnating. The process used at present for impregnating cables has the effect of sometimes giving the greater dielectric strength and capacity where they are not wanted, namely, in the outer layers of the insulating material. This is due to the fact that the liquid used for impregnating more easily reaches and solidly fills the outer portions of the dielectric. As often manufactured, rubber cables are subject to the same fault; because pure rubber, which is of the lowest specific capacity, is placed next the conductor, the tougher, degraded or vulcanized rubber of greater capacity being used for

the outer layers. While the unequal distribution of dielectric strength is of little importance in itself, there is greater danger of a breakdown than if the insulation were homogeneous throughout, due to the increased capacity created in the outer layers.

Composite Construction. Not with a view to obtaining the results to be secured by "grading" the insulation but primarily for the purpose of reducing the cost, cables have recently been made with rubber and paper, or rubber and cambric insulation combined. By using rubber next to the conductor and paper or cambric outside the rubber, the more expensive and better insulation is distributed where its greater strength is most advantageously used. Attempts have been made to enclose paper insulation with a light jacket of rubber as a protection against moisture; but owing to the difficulty of vulcanizing the rubber without injuring the paper, such results have met with but little success.

Where two or three-phase currents are employed for high-tension work, the several underground conductors required for such a circuit are usually separately insulated, laid up with jute and then the whole enclosed in a "jacket" or "belt" of insulating material, which further insulates, to ground, economizes space and insulation and especially protects mechanically. For full working potential between conductors and ground, the "jacket" or "belt" is, particularly with paper and cambric, usually equal in thickness to the insulation about each conductor; in case of star-connected circuits

with grounded neutrals, the insulation between conductor and ground need be, theoretically, but six-tenths that between conductors, practically, however, it is made somewhat heavier than theory would require.

At present there seems to exist a well-founded feeling that too much money has been expended in, and too high an electrical value placed on the "jacket" or "belt," usually employed with high-voltage cables. In considering whether or not it is desirable to use part of the insulation of such a cable in a "jacket" or "belt", or whether the same expenditure for insulation could be better made in thickening the insulation about each conductor, it should be borne in mind that if the "belt" is injured—as will usually be the case if a breakdown occurs—its value is reduced to little or nothing, as supplementing the insulation about the two other conductors, which may be uninjured. This reasoning relates to electrical considerations and does not include the mechanical advantages obtained by the application of a second separate and distinct layer of insulation which affords a smooth, even surface for the application of the lead sheath, and withal makes the cable more flexible. It would seem as if a lighter belt and heavier insulation about each conductor would be more advantageous than the present general practice of making the belt and the insulation about each conductor of the same thickness per thousand volts of potential stress.

Concentric cables consisting of a rod, insulated, and

inserted in one or two metal tubes, as the second or third conductor, were early employed, particularly abroad; but have hardly demonstrated their claims to superiority; their use is being restrained, in Germany, for example, being prohibited for voltages over 3,000. For low voltage work, concentric cables offer some advantages which are extending the use of such cables in America. On account of the increased thickness of insulation required with higher potentials, say from 50,000 volts upward, single conductor cables will probably be necessary for such potentials, at least when they are to be much handled or drawn in ducts.

Thickness of Commercial Insulations. Various formulae have been suggested by which to determine the proper thickness of the different insulations to use for a given potential. Such formulae usually contain empirical constants, the value of which largely depends on a personal equation. The errors caused by the practical difficulties of manufacture, such as eccentric placing of the insulation about the wire, unevenness of application, imperfections in the dielectric, mechanical considerations of strength, make tables of insulation required for different voltages and sizes of conductors, much more valuable and reliable, than formulae, as the former are based on practical experience, tests and guarantees that manufacturers are willing to stand back of.

In determining the thickness of insulation of high-tension cables, whether from the standpoint of theoretical design or consideration of actual installations, it

must be borne in mind that quantity gives no indication of the quality of dielectrics. Furthermore, the normal voltage at which a cable may be expected to be operated gives little indication of the monetary or dielectric values of the insulation used; these values are determined rather by the factor of safety employed and the breakdown or puncture tests which the cables must pass. The superiority of a given character of insulation furnished by one manufacturer as compared with that of another manufacturer for a given service, of necessity compels relegating to a secondary consideration the question of mere thickness of a dielectric. As one manufacturer has expressed it, "puncture tests rather than working voltage, or thickness of insulation, is what we want specified." Nevertheless, the following information is here submitted, not as indicating the minimum limiting thickness of the best grade of insulation for the voltages specified, but as showing in a general way what some representative manufactures are offering, and as a conservative guide to what can reasonably be asked and obtained.

Mr. H. G. Stott states that from his experience, paper insulation for 3,000 volts on wires from No. 6 to No. 00 B. & S., inclusive, should be 5/32 of an inch thick, and for larger sizes up to 300,000 c. m., 6/32 of an inch thick with an increase of 1/32 inch for each 1,000 volts up to 11,000 volts and after that 1/64 inch additional insulation for each 1,000 volts. For 35 per cent Para rubber compound or varnished cambric, he states that it is only necessary to add 1/64 inch

additional insulation for each 1,000 volts above 3,000 until 25,000 volts is reached.

The General Electric Company, Schenectady, N. Y., for three-conductor stranded, varnished-cambric insulated, leaded cables, recommending the same thickness of insulation about each conductor as in the jacket, give the following figures:

***TABLE II.**

THICKNESS OF CAMBRIC INSULATION.

(G. E. CO.)

Normal Working Voltage	Insulation about each Conductor	Insulation about three Conductors
7,000	4/32 inch	4/32 inch
10,000	5/32 "	5/32 "
13,000	6/32 "	6/32 "
17,000	7/32 "	7/32 "
20,000	8/32 "	8/32 "
23,000	17/64 "	17/64 "
25,000	18/64 "	18/64 "

*General Electric Co. Bulletin No. 4591.

The Safety Insulated Wire & Cable Company, New York, specify the following thicknesses for rubber (30 per cent Para), and paper insulated cables, they do not furnish varnished-cambric insulation.

It will be noted that no jacket is provided with the rubber-insulated cables intended for use at the lower

potentials, this is due to the fact that a thin rubber jacket will be relatively largely reduced in thickness by the pressure from the insulated conductors, as it seems impossible, practically, to maintain uniform pressure of the jute filling and the conductors against the jacket.

TABLE III.

THICKNESS OF RUBBER AND PAPER INSULATION.

(S. I. W. & C. CO.)

Normal Working Voltage	Rubber Insulation		Paper Insulation	
	About each Conductor	About three Conductors	About each Conductor	About three Conductors
5,000	5/32 inch	None	4/32 inch	4/32 inch
7,000	7/32 "	None	5/32 "	5/32 "
10,000	5/32 "	5/32 inch	6/32 "	5/32 "
13,000	7/32 "	5/32 "	7/32 "	6/32 "
17,000	8/32 "	5/32 "	7/32 "	7/32 "
20,000	9/32 "	6/32 "	8/32 "	8/32 "
25,000	10/32 "	7/32 "	10/32 "	10/32 "
30,000	12/32 "	10/32 "	12/32 "	12/32 "

Pirelli and Company, Milan, Italy, usually employ impregnated paper for cables up to 20,000 volts; for higher pressures they employ their own special system of india-rubber and paper insulation. As indicating in a very general way their practice, the following figures are given:

TABLE IV.

THICKNESS OF PAPER INSULATION.

(P. & CO.)

Normal Working Voltage	Total Thickness of Insulation
10,000	.27 inch
16,000	.38 "
20,000	.50 "

The British Insulated & Helshy Cables, Ltd., Prescot, England, gives the same thickness of insulation on three-conductor cables that is specified by the Engineering Standards Committee, as follows, for medium size conductors:

TABLE V.

THICKNESS OF RUBBER AND PAPER INSULATION.

(B. I. & H. C., Ltd.)

Normal Working Voltage	Rubber Insulation		Paper Insulation	
	About each Conductor	Jacket about star-connected and grounded Conductors	About each Conductor	Belt about star-connected and grounded Conductors
6,600	.21 inch	.10 inch	.24 inch	.18 inch
11,000	.30 "	.11 "	.36 "	.24 "

Most of the above tables are based on full working potentials between conductors or between conductor

and ground. In case the three conductors are used for star-connected circuits with grounded neutrals, the thickness of insulation between a conductor and ground need be but 6/10 of that between conductors, but in practice it is made somewhat thicker than theory dictates. This relation of voltage and insulation should be borne in mind when testing and all tests on the cable should be properly proportioned to the thickness of the insulation.

Joints. The purpose of a paragraph on cable joints is not to teach splicing to those unacquainted with the methods employed, but rather for the purpose of emphasizing the importance of this part of cable installation. Reference has already been made to the generally admitted fact that joints are the weakest points in high-tension cables. This is so not because the joints necessarily need be weak, but because proper attention and care has not been exercised in making them. More breakdowns in cable operation have probably resulted from defective joints than from all other internal causes. Careful and competent work in making joints at the time of installation will later avoid much worry, inconvenience and monetary loss. Except for the largest companies, which can afford to maintain regularly in their employ high grade, experienced cable workmen, it is advisable for all purchasers to include in their contracts with the manufacturers, the drawing-in and jointing of cables complete.

Various types of tape and compound are employed

for making cable joints, depending on the insulation used. For rubber insulated cables usually a layer of pure rubber is applied and then compounded tape is used, which must be vulcanized, after application, by immersion in a bath of suitable hot compound or by means of a torch used only in the hands of an expert, as undue heat applied to rubber tape will injure it. Paper and cambric-insulated cables have their joints wrapped with paper or cotton tape, which may well be kept in the hot compound, which later will be used for filling the lead sleeve. All joint wrapping material left exposed to the air or moisture deteriorates and should be carefully protected. Even the moisture from the hands of the workmen has been known to be sufficient to destroy an otherwise perfect splicing job. No acids should be used as a flux in soldering, as it is liable to injure the insulation.

The secret in making a perfect joint, provided proper materials are furnished, is

(a) Exclude all moisture.

(b) Make the wrappings as tight as possible, to exclude air.

(c) Have the layers of tape overlap and adhere uniformly.

(d) Be certain the compound is sufficiently hot, before pouring.

The insulation in a joint should be made somewhat thicker than that about the conductor. A common rule is to make the insulation at the splice 150 per cent of that about the conductor.

For paper-insulated cables, a special paper tube has been brought out large enough to slip over the insulation about a conductor, so that after the conductors are spliced and taped the tube is drawn over the splice and further tape added; and from the records made, this method of insulating a joint seems to give very satisfactory results, the advantage of having part of the insulation about the joint made up in a uniform and perfect manner in a factory, will be recognized.

The method of making joints, which has resulted in the excellent record of paper cables, referred to on page 35, may be interesting, as no special tools or particularly skilled labor are required. The outside paper belt of the cable is first removed and the jute filler turned back and tied down out of the way. The ends of the conductors are bared and joined by metal sleeves properly sweated on. An insulating compound, manufactured in Chicago, heated to about 150 degrees Cent. (300 degrees Fahr.), is then poured over the conductors to drive out all moisture which may be present, after which strips of treated paper tape are wrapped as tightly as possible about the metal joints to a thickness appreciably greater than that of the insulation about the conductor, paper tubes sometimes being used in connection with tape; the heated compound is also poured over the joint during the wrapping to keep out moisture. When the three joints are completely taped, the filler is turned back to fill the hollows between the conductors; the whole being further wrapped with paper tape to somewhat greater thickness than the

jacket insulation. Holes are punched through the outer wrapping near each end to permit the escape of air and the admission of the compound. The lead sleeve is then slipped over the insulated joint and wiped in the usual manner. The compound, at a temperature of 150 to 175 degrees Cent. (325 degrees Fahr.), is poured through one opening in the lead sleeve until it flows out of the other opening; after standing for a half hour or more, the sleeve is again refilled and then sealed with lead patches. The principal points in the making of this joint seems to be the exclusion of moisture and the use of a compound which will not absorb moisture, has high dielectric strength, will not attack the conductors or their insulations, and careful, thorough workmanship throughout.

After making a joint complete, it is advisable to let it stand for from two to six weeks and then tap the lead sheath and refill it with compound. Experience shows that in joints and end-bells the compound gradually shrinks or works itself away into the insulation so that it is necessary to add additional compound from time to time.

Specifications. Although some suggested form of specification for cable insulation would be appropriate and desirable in a book of this character, the author has purposely omitted any such specifications for the following reasons:

First. General information regarding current practice and the latest developments in the insulating art,

will much better qualify the competent engineer to draw his own specifications best adapted to the especial requirements of his particular case than any general specification that does not attempt to mention the details which are necessary to make specifications of value.

Second. Owing to the different characteristics of the dielectrics used, the wide variance in conditions of installation and voltage operation, any single specification would be too general to be of value and detailed specifications for all conditions would result in almost a book of specifications.

Third. Because of the comparatively brief experience with and relatively inexact knowledge of the properties of the various dielectrics, engineers of standing differ considerably as to the requirements and tests which a given set of specifications should include. Until there is a greater unanimity of opinion than thus far shown—as evinced, for example, by the failure of the committee appointed by the American Institute of Electrical Engineers, to recommend specifications—it is probably desirable that each engineer use his own best judgment.

Fourth. Specifications* for cables insulated with 30 per cent rubber compound, have been agreed upon by representatives of the Engineers' Association. Similar specifications for paper-insulated cables have also been issued by companies engaged in that line of

* Copies of which may be had upon application to almost any of the prominent cable manufacturers.

manufacture. These specifications, having been drawn up by the representatives of the manufacturers, stipulate tests which may fairly be called conservative; but taken in connection with the Standardization Rules of the A. I. E. E., adopted June 21, 1907, are an excellent guide to specification writing.

Practical Commercial Potentials Elaborate calculations have been made by certain engineers tending to show that, on account of the increased cost of insulation with increased potentials, 25,000 volts is as high an e. m. f. as is commercially and financially economical to use in underground transmission. In order to check these theoretical conclusions it is only necessary to compare the bona fide prices of cables that may be obtained for different voltages. An examination of the curves (see Fig. 4), which are based on recent quotations, shows that as great advantage can be obtained by increasing the potentials from 20,000 or 25,000 volts to 30,000 or 35,000 volts, as is gained by increasing the voltage from 10,000 or 11,000 volts to 20,000 or 25,000 volts. This is so because the cost increases in the same ratio as the voltage, both below and above 25,000 volts, as indicated by the curves being straight lines. The practical limits to continued increase in voltage are the mechanical difficulties, the most obvious being:—

(a) Handling cables of such great diameter as would result from the use of even the best dielectrics at present known.

(b) Necessity for the use of larger ducts requiring special construction.

Inside measurements of the larger vitrified ducts generally used at present, are about $3\frac{1}{2}$ inches, this dimension, therefore, determines, as about 3 inches the maximum diameter of cable that can be used, allowing for necessary play in drawing in the cable. As a general proposition there is no reason why 4-inch vitrified ducts should not be installed in many large cities, as the increased expense would be but an inappreciable percentage of the total cost of the complete conduit and the future advantage may be considerable. The tendency in this direction is indicated by the recent availability of ducts having an inside diameter of about 4 inches. Another difficulty to be overcome in exceeding the diameter of 3 inches for a completed cable, is found in the leading machines at present available, which cannot handle a cable much larger than 3 inches in diameter.

Assuming three inches as the limit of the outside diameter of a complete cable to be installed in standard three and one-half inch ducts, or three and three-eighth inches for the cable with four inch ducts, which are now regularly in stock, and accepting dielectrics at present used, it may be both practically and commercially advisable, even with an advance over present prices of lead, copper and insulating materials, to employ as high as 35,000 volts for underground transmission. With improved or "graded" dielectrics, provided the amount of power being transmitted does not

require the use of conductors of too large cross-section, three-conductor cables for higher than 35,000-volt service would seem advisable. Under certain conditions, as in the case of underground connection between a substation in the centre of a city and the end of a high-tension aerial transmission line operating at 50,000 volts or 75,000 volts, the use of such voltages on single-conductor underground cables could be recommended.

> "On comparatively short lengths under ground or under water, as a part of a long overhead transmission line, cables operating at 40,000 volts can be used."*

The use of single-conductor cables for the higher voltages means a very appreciable increase in cost as compared with a three-conductor cable for the same voltage, enclosed in a single lead sheath. A compensating advantage, however, in the use of separately insulated conductors is, that fewer reserve conductors need be installed. For example, five single conductors, each in a separate duct, would probably afford as much reserve insurance as two three-conductor cables, because, in case of a burnout in a three-conductor cable, the use of the entire cable would ordinarily be discontinued; whereas, with single-conductor cables, in separate ducts, one or two cables could burn out leaving the third for use with the other two reserve conductors.

* Proceedings A. I. E. E., January, 1909, page 14.

From the quotations hereafter given on the three-conductor, lower voltage cables, say 25,000 volts, and the single conductor, higher voltage cables, for example, 50,000 volts, it can be shown that where large blocks of power are to be transmitted, the higher voltage cable installation will cost less than that the lower voltage, without considering some slight advantage to be gained by the installation of fewer ducts and the less cost of drawing in and connecting the single conductor cables.

The liability of an increased rate of depreciation in the use of cables operating at higher potentials must properly be considered. This increased risk is due to electrostatic effects and the liability of decomposition in other than inactive organic substances used in the insulating material. Although these questions have not yet been scientifically investigated, the use and operation of cables designed for 25,000 volts has shown no abnormal depreciation. An 800 ft. section of the 25,000-volt rubber insulated cable installed at St. Paul was recently returned for re-sheathing (necessary by reason of the destruction of the sheath by electrolytic action of street railway currents), which showed the insulation was in every respect as good after seven years of continuous operation as when first installed.

Chapter V.

METAL IN CABLES

Copper. Copper is used almost exclusively as the transmitting medium for electricity because of its strength, malleability, ductility, conductivity and relatively low price. For aerial circuits, aluminum has been used to some extent, but thus far, scarcely at all for insulated conductors. Practically all of the copper used for electrical purposes has been refined electrolytically, and when soft and annealed has a conductivity close to unity, as compared with Dr. Matthiessen's standard; hard drawn copper has somewhat greater resistance than soft copper. The usual wire specifications of 98 per cent pure is appreciably under what may be required of ordinary, commercial, refined copper.

The elastic limit of copper ranges from about 7,000 pounds per square inch with .168 inch soft drawn wire, for example, to about 40,000 pounds per square inch with .1046 inch hard drawn wire; that is, from 22 per cent of the ultimate tensile strength in the first instance to 60 per cent in the last instance. These figures must be taken as approximate, because the elastic limit varies with the amount of drawing and hardening the sample has received. Perhaps what is more important than elastic limit in a copper conductor, is the tensile

strength, which for annealed copper is usually taken at about 30,000 pounds per square inch, and for hard drawn copper, at about 60,000 pounds per square inch at 70 degrees Fahr. The range of temperature encountered in the practical operation of underground cables is too small to have any material effect on the tensile strength of copper.

TABLE VI.

COMMERCIAL BARE COPPER SOLID WIRES.

Size B & S.	Area C. M.	Diam. Inches	Resistance at 68° F. Ohms per 1 000 ft.	Breaking Weight Lbs.	Breaking Weight Lbs. per sq. in.
6	26,250	.162	.3944	1,221	59,300
5	33,100	.181	.3128	1,520	58,500
4	41,740	.204	.2480	1,890	57,600
3	52,630	.229	.1967	2,338	55,600
2	66,370	.257	.1560	2,892	55,500
1	83,690	.289	.1237	3,565	54,200
0	105,500	.324	.09811	4,386	52,900
00	133,100	.364	.07780	5,365	51,300
000	167,800	.409	.06170	6,533	49,500
0000	211,600	.460	.04893	7,914	47,600

On account of rigidity, larger copper conductors are made up in the form of a stranded cable, consisting of a number of smaller wires. This construction results in a somewhat higher elastic limit, greater tensile strength and larger diameter, as compared with solid wire. Any number of wires can be laid up to form a

cable, but the size of the individual strands and the method of laying them up so as to secure the simplest, most compact, most flexible and least expensive construction is the result of considerable experiment and experience. In the construction of conductors for un-

TABLE VII.

COMMERCIAL BARE COPPER STRANDED WIRES.

Size of Conductor in C. M.	Number of Strands	Diam. of Strands in Inches	Diam. of Cables in Inches	Resistance at 68° F. Ohms per 1,000 ft.
4	7	.0771	.231	.2480
3	7	.0866	.260	.1967
2	7	.0975	.292	.1560
1	19	.0663	.332	.1237
0	19	.0746	.373	.0981
00	19	.0837	.419	.0778
000	19	.0941	.471	.0617
0000	19	.1055	.528	.0489
250,000	37	.0821	.575	.0414
300,000	37	.0900	.630	.0345
350,000	37	.0972	.680	.0296
400,000	37	.1039	.727	.0259
450,000	37	.1103	.772	.0230
500,000	37	.1163	.815	.02071

derground cables layers of copper wires are placed around the core with a slight spiraling, then additional layers are added alternately spiraled in opposite directions, until the desired cross-section is obtained. This arrangement, while not quite as flexible or possessing quite the tensile strength of strands made up into ropes

and the several ropes combined in a cable permits the maximum economy in applying the insulation. Con-

TABLE VIII.

APPROXIMATE OUTSIDE DIAMETERS OF THREE-CONDUCTOR COPPER CABLES.

(⅛ Lead Throughout)

Insulation Thickness on Each Conductor, and Over Bunch Respectively Equal to

SIZE	5/32 + 5/32	6/32 + 6/32	7/32 + 7/32	8/32 + 8/32	10/32 + 10/32
	Diam.	Diam.	Diam.	Diam	Diam.
4	1,735	1,930	2,129	2,324	2,717
3	1,795	1,990	2,189	2,384	2,777
2	1,864	2,059	2,258	2,453	2,845
1	1,950	2,145	2,344	2,539	2,933
0	2,038	2,233	2,432	2,627	3,020
00	2,137	2,332	2,531	2,726	
000	2,246	2,442	2,640	2,839	
0000	2,371	2,567	2,765	2,960	
C. M.					
250,000	2,472	2,668	2,866		
300,000	2,588	2,785	2,983		
350,000	2.700	2,895			
400,000	2,803	3,000			
450,000	2,898				
500,000	2,988				

ductors of large cross-section are inadvisable for alternating currents, unless subdivided into several ropes, or even separate cables, on account of "skin effect," induction and increased ohmic losses due to the greater length of the spiralled strands, which the current follows.

Aluminum. The relatively large diameter of aluminum conductors compared with those of copper, where the prices for equal conductivity in these metals have been maintained fairly closely—as has been the case in this country—has prevented any extended use of insulated aluminum conductors. The expiration, at about this time, of the patents which contain the fundamental claims covering the production of aluminum and the recent dissolution of the agreement holding up prices in Europe, has resulted in a marked drop in prices of aluminum, both abroad and in America, with every prospect of a continued range of prices being maintained at a lower level than ever before. The result is that the manufacturers of insulated conductors have taken up the furnishing of aluminum cables, which are now available at prices particularly favorable, as against copper cables. For example, a recent quotation on 1,000,000 c. m. copper cable insulated to 4/32 inch with 1/8 inch lead sheath, was given as 76 cents per foot, whereas a 1,600,000 c. m. aluminum cable (having the same conductivity as 1,000,000 c. m. copper), with the same thickness of insulation and sheath, was offered at 65 cents per foot. Such a reduction, of from 12 to 13 per cent in the cost of cable for a given installation, will doubtless result in the wide use of aluminum insulated cables. In the example cited above, the increased diameter of the aluminum cable, as will sometimes be the case, was not objectionable as only one cable would be installed per duct. In the case of the copper cables, the diameter

was 1 5/8 inch, and in the case of aluminum, 2 inches, an increase of 3/8 inch in diameter, which is not sufficient to make the drawing in laborious or injurious. The relatively increased diameter of the aluminum gives an increased heat radiating surface and thus permits a larger current capacity without increasing the "skin effect."

TABLE IX.

COMPARATIVE DIAMETERS OF BARE COPPER AND ALUMINUM STRANDED WIRES HAVING THE SAME CONDUCTIVITY.

Copper			Aluminum		
Cir. Mils.	No. of Strands	O. D. Cable	Cir. Mils.	No. of Strands	O. D. Cable
105,500	19	.373 in.	168,800	19	.470 in.
133,100	19	.419 "	212,960	19	.529 "
167,800	19	.470 "	268,480	19	.595 "
211,600	19	.528 "	338,560	19	.668 "
250,000	37	.575 "	400,000	37	.728 "
300,000	37	.630 "	480,000	37	.797 "
350,000	37	.681 "	560,000	37	.861 "
400,000	61	.729 "	640,000	37	.921 "
450,000	61	.773 "	720,000	37	.977 "
500,000	61	.815 "	800,000	37	1.029 "

To facilitate the use of aluminum cables, which cannot be very satisfactorily soldered, improved methods of jointing have been developed. A particularly successful form of joint is known as the "compression

joint," which is a sleeve carrying enlargements that are forced to flow into and among the strands of the cable by means of a small hydraulic press, so that when complete the conductivity of the joint is as good as that of the cable itself.

As there is one particular diameter of copper conductor which is cheapest for each given voltage, it follows that if less power is being transmitted than corresponds to the proper diameter for the voltage assumed, or if potential stress at the inmost layer of the insulation exceeds the dielectric strength of the material—so that the insulation will break down—it is evident that aluminum could be profitably substituted for a copper conductor.

The coefficient of expansion of aluminum and lead are nearly alike thus making them valuable to associate together in cable manufacture, in order to avoid internal strains by reason of change in temperature.

Tin and Lead. In insulating copper conductors with rubber, it is usually considered necessary to tin them in order to prevent any free sulphur left in the rubber from attacking the copper. To this same end a thin layer, 1/64 to 1/32 of an inch in thickness, of soft, pure rubber or rubber compound containing no sulphur, is used by some manufacturers, next the conductor, as an additional preventive in keeping the sulphur away from the copper. With any except conductors of very small diameter, this use of pure rubber is probably a needless expenditure of care and money; because, if the con-

ductor is carefully tinned and the rubber properly vulcanized the chance for sulphur's attacking the copper is very small on two accounts: first, even if there were imperfections in the tin and the sulphur gets through the imperfections, the amount of copper degraded will be so small relatively that the conductivity of the conductor—except with possibly the very smallest conductors—will not be reduced, as a practical matter; and second, the amount of free sulphur in properly vulcanized rubber insulation is so small that with conductors of large cross-section even not tinned at all, the extent of damage to same would probably be immaterial. With paper, where no sulphur is present, tinning is not necessary and is not resorted to. With cambric insulation, a "separator" of neutral material is employed to prevent anything in the varnish attacking the copper.

Some tin is usually alloyed with the lead used for the outside sheath. Lead alloyed with tin makes a harder sheath and one less liable to injury from contact with the sharp projections or edges encountered in drawing into conduits. The amount of tin specified for cable sheathing is usually not less than 1 per cent or more than 5 per cent. As a practical matter, 1 per cent is a rather small quantity and 2 per cent as a minimum with 3 per cent as a maximum make desirable alloys; 5 per cent is apt to make the sheath too stiff and brittle. In some instances, purchasers require that the lead sheath be dipped in a tin bath, with the evident purpose of making a hard exterior, which, while affording a finished surface, is probably too thin to prove much of

a mechanical protection, but which doubtless fully protects lead against carbonic acid gas or other deleterious products which may attack the lead, and is therefore desirable under certain conditions of installation.

Chemically pure lead is both relatively expensive and difficult to secure, it is so soft and would so soon become friable and weakened by combination with carbonates or other deleterious substances that the commercial lead, which usually contains some antimony and other impurities, is fortunately a much better material.

The proper thickness of lead sheath varies somewhat with the character of service to be met and the type of insulation employed: but particularly, with the size and weight of cable on which the sheath is used. For small rubber or cambric insulated cables, 1/16 inch lead is a sufficiently heavy sheath, while perhaps something thicker in the case of paper insulation should be employed. With large insulated cables, it may be necessary to use a sheath as thick as 3/16 inch, but anything heavier than this is apt to make a very stiff cable. A sheath, 1/8 inch thick will be found satisfactory for the usual weights of cable, and normal conditions of underground installation.

As the lead sheath is put on cables for the purpose of protecting the insulation, it is essential that the lead be applied with uniform thickness and absolute freedom from imperfections in its continuity. If the temperature of the lead in the leading machine is too high, the insulation is not only likely to be injured, but the

sheathing will not be uniform; and if the temperature is too low, the sheathing is apt to contain air holes or split when the cable is bent. As the chain is only as strong as its weakest link, the absolute integrity of the lead sheath, particularly with paper insulated cables, is absolutely essential.

The lead sheath is really a more delicate part of a cable than is usually considered, because it is rather weak mechanically, easily destroyed by electrolysis, disintegrated by mechanical action or relatively small temperature rises, and attacked by at least one insect found both abroad and in the United States. It has been claimed that 90 per cent of all failures of underground cables has resulted from breakdowns of one sort or another, in the lead sheaths.

Two or more conductors of the same circuit should always, if possible, be placed under the same lead sheath, because currents induced in the lead circulate through the points of contact of the respective cable sheaths, causing heating or arcs liable to damage the lead or cause explosions from accumulated gases. The energy losses in lead sheaths have been investigated by Morris of England and Dr. Monasch. The former found that with a given wave form and cable they varied directly as the length and .7 power of the thickness of sheath and as the square of current and frequency, and for "a three-core cable carrying 50 amperes per phase with a frequency of 60 periods and with a thickness of insulation between each conductor .35 inch, and thickness of sheath .125 inch, the loss in the lead sheath

was 17 watts per mile," or with the ordinary commercial three phase transmission the sheath loss is an unimportant percentage of the total energy considered. On the other hand single conductor cables carrying alternating currents may have large voltages and resulting currents induced in their sheaths. Fisher* reports having obtained "from 15 to 30 volts per 1,000 ft. with an ordinary lead-covered cable, and in the case of a steel-wire armored cable the lead volts per 1,000 ft. were 100" and armoured with "two wraps of steel tape, 350 volts." Under such conditions the advisability of frequent grounding of sheath or armor is evident.

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*Proceedings A. I. E. E., January 1908, page 95.

Chapter VI.

HEATING OF CABLES

Cables versus Wires.* While the diameter of high-tension transmission conductors for aerial work is usually determined by the drop of potential allowable, very frequently the factor controlling the cross-section of underground cables is the permissible temperature rise of the insulation, particularly when a cable is installed in a conduit system consisting of many contiguous ducts. The same causes that limit the carrying capacity of aerial conductors applies to underground conductors; but they are aggravated by the insulation surrounding the conductor.

The current carrying capacity of a cable depends on,

(a) The initial temperature of the medium surrounding or in contact with the cable.

(b) The ability of the surrounding medium to dissipate heat.

(c) The ability of the dielectric and sheath to transmit heat.

As all heat generated in a conductor must be radiated through the surface area, and as this varies as the diameter while the cross-section varies as the square of the diameter, it is seen that the heat radiating surface does not increase anything like as rapidly as the

* The author uses Cables as applying only to insulated conductors, usually lead covered, and wires to bare, aerial conductors, whether solid or stranded.

conductivity or circular milage, the result is that the current carrying capacity (cross-section) is limited by the heat radiating area (surface), and in consequence, all conductors of large size must carry fewer amperes per circular mil than small conductors. With the light insulation required for 600 volt service it has been found, for example, that the practical limit of size, by reason of radiating area, is 2,000,000 c. m.

Bare conductors can usually radiate the heat generated by any current they may be called upon to carry, within limits of commercial drop in voltage. However, on account of its greater radiating area a single conductor cable suspended in air will dissipate the heat generated therein, more freely and maintain a lower temperature than a bare wire similarly located. With cables, however, the method of installation prevents the free dissipation of heat generated, so that their carrying capacity in amperes is relatively largely reduced.

Ignoring the change in resistivity of a conductor, the heat developed per unit of length is constant, whereas the temperature rise is logarithmic; so that in case of a cable carrying a constant number of amperes the temperature first rises rapidly, perhaps 75 per cent of the ultimate temperature within the first hour, and then somewhat slowly, depending in each case on the thermal time constant of the insulating material and reaching the final temperature after three to five hours.

The question of rise of temperature in underground cables is a very vital one, not alone because the insulat-

ing qualities of the dielectric decrease and deteriorate very rapidly with increase in temperature but also because the alternate expansion and contraction of the conductor, dielectric and sheath, with varying loads, tends to mechanically injure the insulation and the sheath, as all three materials have different coefficients of expansion. Instances are reported of the cutting of lead sheaths, resting on the sharp edge of tiled ducts, by alternate lengthening and shortening of a cable due to heating and cooling.

Rise of temperature is particularly important as regards rubber and varnished cambric insulations, the maximum temperature of which for continuous operation should probably not be allowed to exceed about 65 degrees Cent. (150 degrees Fahr.), or assuming the temperature of the earth is 20 degrees Cent. (70 degrees Fahr.,) a rise of 45 degrees Cent. (80 degrees Fahr.) is permissible. Although rubber will transmit heat somewhat more readily than paper, cables with paper insulation have a greater current carrying capacity with a given conductor than when insulated with rubber or cambric; because such paper insulation can be operated at a higher temperature, say 80 degrees Cent. (175 degrees Fahr.)

A. C. vs. D. C. In cables used for continuous currents, heating results only from the I^2R losses in the copper; but in cables used for alternating currents there are additional heat losses due to

(a) effects in the insulating material itself, similar to hysteresis in iron.

(b) losses in the conductor itself or lead or steel sheath due to foucoult currents,

(c) unequal distribution of current density in the cross-section of the conductor, the density increasing at the circumference of the conductor and known as "skin effect."

With alternating currents and high potentials the losses in the insulation may be appreciable; similarly, by reason of heavy currents or thick sheaths the losses in the conductor or sheath (see page 86), may become noticeable; also, with conductors of very large cross-section where the current density is far from uniform, the loss due to this "skin effect" (see page 120), which increases with frequency, and the diameter of the wire, may become serious; but with moderate potentials, small conductors or light-weight sheathing, these losses are usually immaterial.

As determined by Steinmetz and experimentally confirmed by Apt and Mauritius, the energy loss in the dielectric of cables is proportionate to the square of the e. m. f. and independent of the load. It also depends on the frequency, wave form and to some extent on temperature. Mauritius found that the loss in a certain rubber-insulated cable (rubber insulation has considerable higher loss than paper insulation) with 20,000 volts impressed for a cable 60 miles in length, amounted to 28 kilowatts, which, however, is an inappreciable percentage of the energy being transmitted in any commercial installation.

The report of some comparative tests on the New

York Edison Co.'s high-tension cables are interesting in this connection, as showing the greater power loss in rubber as compared with paper insulation.

DIELECTRIC LOSSES IN TRIPLEX CABLES OPERATING AT 6,400 VOLTS, 25 CYCLES.

	Paper Cable	Rubber Cable
Length, ft.	10,935	24,756
Copper, cir. mills	250,000	250,000
Insulation	10/32 in.	10/32 in.
Temperature (about)	80° F.	80° F.
Charging current in amperes, working conditions	0.47	2.16
Total watts lost	245.	3330.
Watts lost per ft.	0.0224	0.1345

Carrying Capacity. Although various formulae have been proposed to determine the current capacity of cables, they depend on empirical constants, so that while the published results of experiments are limited, the data and tables based thereon are more satisfactory for general reference.

When two or more conductors are included under one sheath, or several conductors installed in one duct, or when a number of ducts are laid up together, the heat generated is not rapidly transmitted and the temperature of the cables thus installed may rise to an alarming degree. Two conductors under a single sheath will have about 10 per cent less, three conductors about 25 per cent less, and four conductors about 35 per cent less current carrying capacity than the same conductor installed singly. The effect of con-

tiguous ducts on the heating of cables is discussed on page 104.

In connection with the following data relating to safe carrying capacity of cables, it must be borne in mind normal conditions are assumed, that an installation in proximity to steam pipes, or in a conduit of many loaded ducts, will reduce the values given, while for a cable laid across the bottom of a deep river, the values are 40 to 50 per cent too small.

Tests under the direction of Mr. Louis A. Ferguson, Vice President of the Commonwealth Edison Company, Chicago, Ill., demonstrated that concentric cables have less carrying capacity than twin conductor cables of the same conductivity. The following curves are taken from his paper,* and though the result of measurements, shown in Fig. 1, are based on paper insulation only 4/32 inch thick, too light for high potential service, they are interesting and valuable. The measurements were made on lead sheathed cable installed in a single duct of vitrified clay pipe, surrounded on all sides with approximately six inches of sand.

The data determined by Mr. Ferguson agrees very satisfactorily, when allowance is made for a cable with different insulation in a single duct, with measurements made by Mr. H. W. Fisher, Chief Engineer of the Standard Underground Cable Company, Pittsburg, Pa., who carried on some elaborate experiments to determine the heating of cables, under his Company's direc-

*"Underground Electrical Construction" Proceedings International Electrical Congress of St. Louis, 1904.

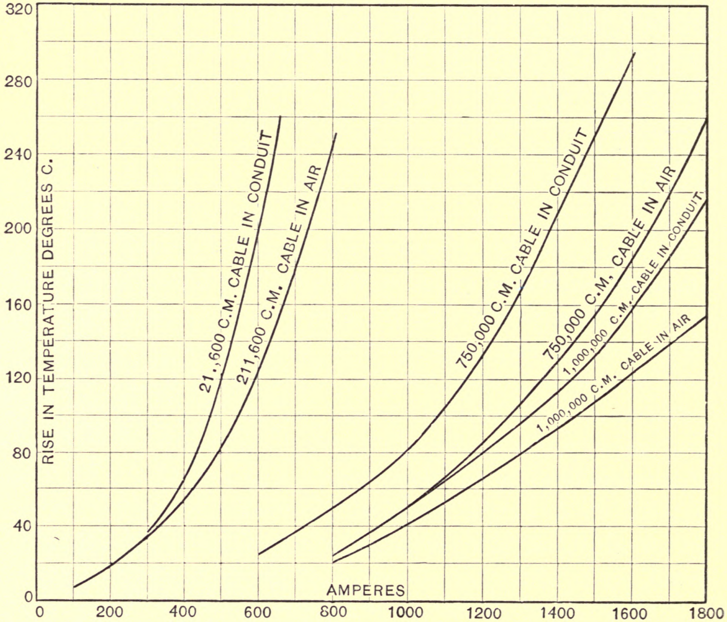

FIG. 1—Relation between current and temperature of single conductor cables insulated with $\frac{4}{32}$ inch paper, sheathed with $\frac{1}{8}$ inch lead, in duct.

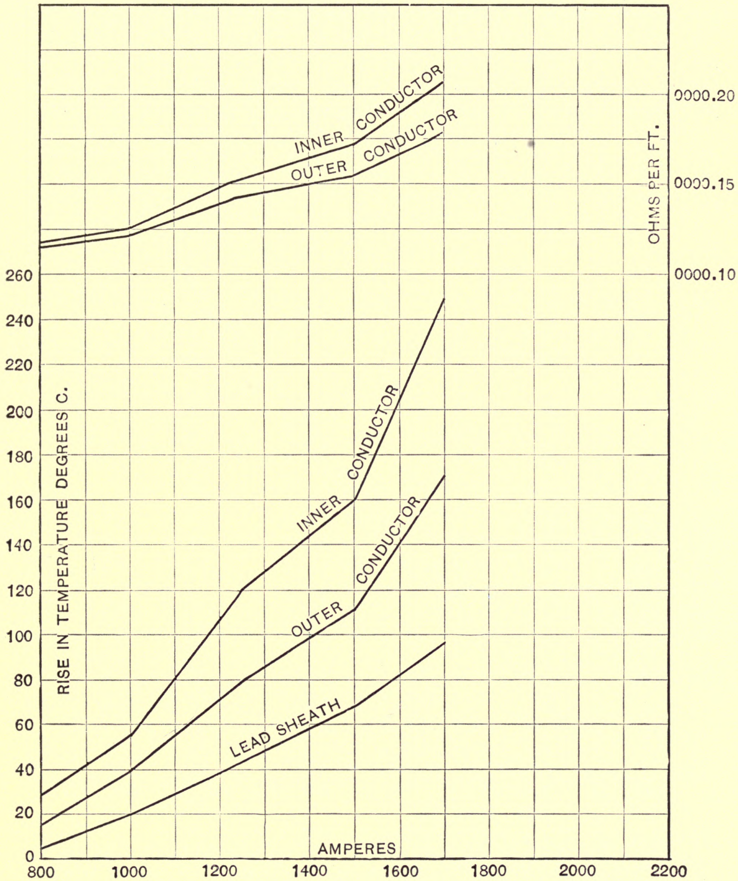

FIG. 2—Relation between increasing current, in two conductor, 1,000,000 c. m. concentric cable, in air and rise in temperature and increase in resistance. Inner paper wall, $\frac{6}{32}$ inch ; Outer paper wall, $\frac{5}{32}$ inch ; Lead sheath, $\frac{1}{8}$ inch.

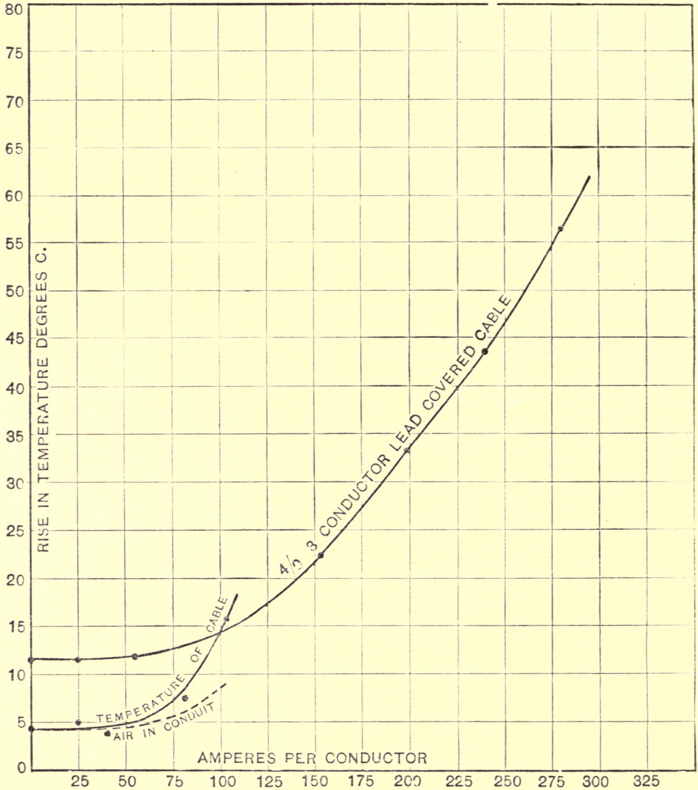

FIG. 3—Relation between current and temperature of three conductor cable, insulated with $\frac{6}{32}$ inch paper over each conductor and $\frac{4}{32}$ inch paper belt, $\frac{1}{8}$ inch lead. In the lower left hand corner is shown the relation between current and temperature of a No. 0 three conductor cable, insulated and sheathed the same as the No. 0000 cable. Both tests were in ducts, in cold weather, other cables in the same conduit were not heavily loaded.

*TABLE X.

RECOMMENDED CURRENT CARRYING CAPACITIES FOR CABLES AND WATTS LOST PER FOOT.

For each of four equally loaded single-conductor cables insulated with 7/32 inch paper and having 9/64 inch lead covering, installed in adjacent tile ducts in the usual type of conduit system four ducts wide and three high, where the initial temperature does not exceed 70 degrees Fahr., the maximum safe temperature for continuous operation being taken at 150 degrees Fahr. The figures in the table may be taken as practically correct for cables insulated with 7/32 inch rubber or varnished cambric, except that temperatures will then be about 125 degrees Fahr. instead of 150 degrees Fahr.

Size B. & S. G.	Safe Current in Amperes	Watts lost ** per ft. at 150° F.	Size C. M.	Safe Current in Amperes	Watts lost ** per ft. at 150° F.
14	18	.97	300,000	323	4.22
13	21	1.03	400,000	390	4.61
12	24	1.09	500,000	450	4.91
11	29	1.15	600,000	505	5.16
10	33	1.25	700,000	558	5.36
9	38	1.39	800,000	607	5.56
8	45	1.53	900,000	650	5.71
7	53	1.67	1,000,000	695	5.86
6	64	1.85	1,100,000	740	6.01
5	76	2.08	1,200,000	780	6.13
4	91	2.31	1,300,000	820	6.25
3	108	2.54	1,400,000	857	6.37
2	125	2.77	1,500,000	895	6.49
1	146	3.00	1,600,000	933	6.61
0	168	3.23	1,700,000	970	6.73
00	195	3.46	1,800,000	1010	6.85
000	225	3.69	1,900,000	1045	6.97
0000	260	3.92	2,000,000	1085	7.09

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**This column represents the amount of energy which is transformed into heat and which must be dissipated.

tion. The formulae and tables given in the Handbook of the Standard Underground Cable Company, have been found to give excellent satisfaction in practice and are here reproduced in part, through the courtesy of that Company.

For a single conductor of the size given in Table X, two or more conductors of smaller size may be substituted, as shown in Table XI, owing to the fact that for the same temperature rise, more current can be carried by using divided circuits.

*TABLE XI.

EQUIVALENT CONDUCTOR AREAS.

B & S. G. No.	In 2 conductors	In 4 conductors	In 8 conductors	In 16 conductors	In 32 conductors	In 64 conductors
0000	No. 0	No. 3	No. 6	No. 9	No. 12	No. 15
000	1	4	7	10	13	16
00	2	5	8	11	14	17
0	3	6	9	12	15	18
1	4	7	10	13	16	......
2	5	8	11	14	17	......
3	6	9	12	15	18	......
4	7	10	13	16	......	......
5	8	11	14	17	......	......
6	9	12	15	18	......	......
7	10	13	16	......	......	......
8	11	14	17	......	......	......

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*TABLE XII.

RECOMMENDED POWER CARRYING CAPACITY IN KILOWATTS OF DELIVERED ENERGY.

THREE-CONDUCTOR, THREE-PHASE CABLES.

Size in B. & S. G.	Volts 4,000	6,600	11,000	13,200	22,000	26,400
	Kilowatts					
6	333	549	915	1,098	1,831	2,196
5	395	652	1,087	1,304	2,174	2,608
4	473	781	1,301	1,562	2,603	3,124
3	562	927	1,544	1,854	3,089	3,708
2	650	1,073	1,788	2,145	3,575	4,290
1	759	1,253	2,088	2,506	4,176	5,012
0	874	1,442	2,402	2,884	4,805	5,768
00	1,014	1,674	2,788	3,347	5,577	6,694
000	1,172	1,931	3,217	3,862	6,435	7,724
0000	1,352	2,231	3,717	4,462	7,435	8,924
250,000	1,503	2,480	4,132	4,960	8,264	9,920

SINGLE-CONDUCTOR CABLES, A. C. OR D. C.

Size in B. & S. G.	Volts 3,300	6,600	11,000	13,200	22,000	24,600
	Kilowatts					
6	211	422	704	844	1,408	1,688
5	251	502	836	1,004	1,672	2,008
4	300	601	1,001	1,202	2,002	2,404
3	356	713	1,188	1,426	2,376	2,852
2	413	825	1,375	1,650	2,750	3,300
1	482	964	1,606	1,928	3,212	3,856
0	554	1,109	1,848	2,218	3,696	4,436
00	644	1,287	2,145	2,574	4,290	5,148
000	743	1,485	2,475	2,970	4,950	5,940
0000	858	1,716	2,860	3,432	5,720	6,864
300,000	1,066	2,132	3,553	4,264	7,106	8,528
400,000	1,287	2,574	4,290	5,148	8,580	10,296
500,000	1,485	2,970	4,950	5,940	9,900	11,880
600,000	1,667	3,333	5,555	6,666	11,110	13,332

As Table X is based on an initial temperature of 70 degrees Fahr., in the surrounding medium, the capacities therein must be corrected by the multipliers given hereafter for initial temperatures, as follows:

Initial Temp...	70	80	90	100	110	120	130	140	150
Multipliers, ..	1.00	.93	.86	.78	.70	.60	.48	.34	.00

While the carrying capacities given in Table X may seem small, it should be remembered that they are for four cables in adjacent ducts; and if less than four cables are to be considered, a correction as follows should be applied which will give carrying capacities more nearly in accord with those generally recognized.

No. Cables,	1	2	4	6	8	10	12
Multipliers,	1.30	1.16	1.00	.88	.79	.71	.63

The cable in the corner duct has, of course, the best carrying capacity, next those in the side ducts and then those in the internal ducts in the order of their proximity to the outside.

The power factor assumed in Table XII is 1.00, and the values must be corrected, for alternating currents, by multiplying the kilowatts given by the power factor of the delivered load. The figures are based on the same data as Table X, namely, paper-insulated lead-covered cables installed in adjacent 3-inch standard vitrified ducts arranged four wide and three high in section with an initial temperature not exceeding 70 degrees Fahr. and allowing a maximum final temperature for continuous operation of 150 degrees Fahr. The measurements were made on cables having 14/64 inch paper about each conductor and with the multiple con-

ductor cables a jacket of 14/64 inch around the bunch. Each increase of 2/64 inch above 14/64 inch in the thickness of the insulation used would reduce the amperes or kilowatts given in the tables by about 1 per cent. The losses figured are the I^2R losses with R as the resistance of the conductor at 150 degrees Fahr. No insulation or sheathing losses are included.

The following information is given by the General Electric Company concerning the temperature rise allowable in three-conductor high-tension cables carrying 60-cycle alternating-current. It will be noted that a definite number of amperes is given and the temperature rise resulting therefrom, apparently deduced. It may be said that the number of degrees rise in temperature allowed in this table is conservative, and the ultimate heating allowable is appreciably less than is being permitted by many operators, at least of rubber and paper cables. The figures in the table are based on insulation not exceeding 7/32 inch thick about each conductor with a jacket 7/32 inch thick over the bunch, and with a lead sheath, 1/8 inch thick over the whole. In connection with this table it may be well to again call attention to the fact that while paper insulation may not transmit heat as readily as rubber or cambric, it may be operated at a higher temperature without detriment, so that the carrying capacity of a given conductor enclosed in paper is as great or in some cases 10 per cent greater, than when insulated with rubber or cambric.

The most economical size of cable conductor to use

has been stated by one writer* as that which shall have a cross-section between .1 and .15 sq. in. (between 125,-000 and 190,000 c. m.) for three-core cables. This con-

*TABLE XIII.

CURRENT CARRYING CAPACITY OF INSULATED THREE-CONDUCTOR CABLES IN DUCTS.

(Initial Temperature, 20° C.)

Size of Cable in Circular Mils	Rubber and Var. Cam. 30° C. Rise Paper, 35° C. Rise
	Amperes on each Conductor
500,000	440
400,000	360
300,000	290
250,000	250
200,000	210
150,000	175
125,000	140
100,000	125
80,000	110
60,000	85
40,000	60
6 B. & S. solid	40
8 B. & S. solid	24
10 B. & S. solid	16

clusion being reached on the ground that "it is more economical in first cost per kilowatt transmitted to

* Proceedings A. I. E. E., vol. XXVIII., Page 91.

transmit a certain amount of power by means of a cable of this section working at a sufficiently high pressure to enable it to carry the required quantity of power than by any other section or voltage." The deduction is based on the fact that a small cable can be worked at a considerable higher current density than a large one, for the same temperature rise.

Temporary Loads. From what has preceded it will be recognized that due consideration of the character of load to be carried by the cable must be carefully considered by the designing engineer, if he is to reduce installation costs to the minimum. A cable capable of carrying a steady rated load current may be amply large to carry for brief periods,—for example, the peak load of a lighting station—a current which is a very considerable percentage greater than the average load. For such intermittent load service, formulae have been developed by Mr. R. Apt.* for single and three conductor cables and by Mr. William A. Delmar;† applicable, however, only to cables smaller than No. 00 B. & S., or insulated for not over 1,000 volts; from which it is possible to determine the overload possibilities of a cable.

When intermittent load service is contemplated, curves of safe time-current for such cables should be furnished by the manufacturer.

* Elektrotechnische Zeitschrift April 18, 1908.

† "Short Period Carrying Capacity of Cables", Electrical World, December 12, 1908.

Ducts. The composition of the duct material will, to a slight degree, affect the carrying capacity of cables. Vitrified ducts conduct away the heat generated in the cables somewhat more rapidly than wood fibre or paper ducts; but this difference is minimized and practically may be ignored where the thickness of the concrete enclosing the ducts is one-half inch in thickness or over. What is a more important factor is the medium surrounding the conduit system. The best heat transmitting material apt to be encountered being water-soaked ground or the water itself, where cables are laid on the bottom of rivers; the poorest being dry sand with rock and loam as intermediate.

The arrangement of the ducts relative to one another, is all important where more than four ducts are installed. It will be seen for example, that the centre one of nine ducts, laid three on a side, can only dissipate the heat generated therein through the other ducts, and a cable in such a duct will have about 10 per cent less current carrying capacity than one in a corner duct. For the same relative position—outside or inside—the top ducts are always the warmest, on this account a horizontal arrangement is preferable. The most desirable arrangement would be a single horizontal layer of ducts, but practically, this would increase the expense disproportionately, so that ordinarily, ducts are arranged two or three wide and to the depth necessary.

As a protection against accumulations of gas, and also with a view to increasing the carrying capacity of

cables, it has been proposed to ventilate ducts by the use of electrically driven ventilators. As a general proposition, the expense of artificial ventilation would not be justified: there may be special cases where it will be found advantageous, as is the case with certain types of electrical apparatus, such as railway motors, etc., but, as a practical matter, the difficulty of forcing air into and through ducts, efficiently, is more serious than it would appear.

The necessity of not leaving high-voltage cables exposed in manholes has become generally recognized. It is impracticable to continue duct construction across the manhole, but a very satisfactory substitute is made in the use of spliced tile ducts carried on shelves around the sides of the manhole. The tile is furnished in short, curved pieces to fit the bends of the cable, which it encloses and protects against arcs or mechanical damage during work in the manhole. In some installations asbestos strips about 3 inches wide and 1/8 inch thick are wrapped around the cables and then impregnated with silicate of soda, which hardens and serves as an effective protection to the cable, the whole being further guarded by wrappings of galvanized iron or zinc tape, which, in every case, should be properly connected to the lead sheath to avoid difference of potential and electrolytic action.

Chapter VII.

ELECTRICAL FORMULAE FOR CABLES.

Resistance. The ohmic resistance of a conductor is the same, at identical temperatures, whether used for bare, aerial or insulated, underground transmission. As is well known, the resistance of a conductor varies directly as its length and inversely as its area, being 10 international ohms per mil foot of soft copper at 51 degrees Fahr. The resistance of the conductor of an electric cable is relatively small, usually but a fraction of an ohm per mile, whereas the resistance of the insulation, on the other hand, is relatively large, being measured in millions of ohms (megohms) per mile of completed cable. The ohmic resistance of commercial conductors is conveniently had by reference to wire tables, or may be measured by a Wheatstone Bridge and galvanometer, or by ascertaining the drop in voltage with continuous current in accordance with the well-known formula,

$$R = \frac{E}{I}$$

Where R equals the total resistance in ohms, E equals the drop in potential, through the length of the circuit, I equals the current flowing, in amperes.

The approximate resistance in ohms per mile of a copper conductor, having 100 per cent conductivity, at 20 degrees Cent. (68 degrees Fahr.), is equal to 54,700 divided by the circular mil cross-section of the conductor. This product should be multiplied by 1.62, in order to obtain the resistance of an aluminum conductor of the same size.

The insulation resistance of a cable varies widely, depending on the thickness and quality of the dielectric employed, being as high as 2,000 megohms per mile for rubber insulation and as low as 20 megohms per mile for paper insulation. The determination of dielectric resistance is made by the use of a galvanometer and Wheatstone's Bridge in the usual manner.

Inductance. An electrical current flowing through a conductor creates a magnetic flux about the conductor, which changes with change in the strength or direction of flow of the current. Any change in the flux produces an electromotive force, the value of which, in volts, resulting from a change in the current at the rate of one ampere per second, has been defined as the unit of inductance, the henry. The effect of inductance is to cause the current to lag behind the electromotive force. Inductance may be measured with a Wheatstone Bridge similarly to ohmic resistance by substituting a standard of inductance for that of resistance.

The inductance for one wire of either single-phase or three-phase circuits—which depends on the size and shape of the circuit, the cross-section and permeabil-

ity of the conductor and surrounding medium—may be calculated for non-magnetic single-phase circuits, by use of the following formula:

$$L = D \left[.08047 + .7392 \log_{10} \left(\frac{d}{r} \right) \right]$$

L equals inductance of a wire, one mile in length, in millihenrys.
d equals distance between centres of wires in inches.
r equals radius of conductor in inches.
D equals length of transmission in miles.

Capacity. The dielectric separating two conductors, maintained at a difference of potential, has the power of holding a quantity of electricity, which property is known as capacity. The capacity of a cable depends on the size and shape of the conductors, the specific inductive capacity of the surrounding medium, and the distance from other conductors. The unit of capacity is the farad (the practical unit, microfarad, is one-millionth of a farad), and is that capacity which will contain one coulomb at a potential of one volt. The effect of capacity on a circuit is to cause a current to flow in advance of the electromotive force. With bare aerial conductors, capacity is usually insignificant, but with insulated underground cables, capacity and its effects become quite marked due to the higher specific inductive capacity of the insulating material and the greater proximity of the conductor to earth.

The effect of capacity is to produce what is called a

charging current, which, in cables entirely overcomes any inductive effects caused by the cables. With long cables and high potentials, the charging current may become so large as to overload the current rating of transformers or generators until an inductive load is supplied.

As an actual example of charging current, the following figures from the St. Paul, 25,000 volt paper-insulated cable, nearly three miles long, are interesting. Measurements were made by a hot wire ammeter in series with one of the three cable conductors, and were 1.8 amperes at 15,000 volts, or .63 amperes per mile, 2.4 at 20,000 volts, or .84 amperes per mile, and 3.0 amperes at 25,000 volts, or 1.06 amperes per mile, the curve of relation between current and applied potential being a tangent. The voltage was supplied from a three-phase generator through step-up transformers with no other load than the cable being tested. Measurements on the rubber cable showed practically double the current in amperes obtained from the paper cable, corroborating the testimony of other observers as to the relative capacity of paper and rubber insulated cable.

The electrostatic capacity of a single conductor cable as measured between the conductor and the lead sheath per mile may be expressed, in microfarads, by the following formula:

$$C = \frac{.0388\ K}{\log_{10} \frac{R}{r}}$$

The total charging current for a single-conductor cable equals:

$$\frac{2 \pi f C E D}{10^6}$$

For obtaining the total capacity per mile, per wire of a three-conductor lead-covered cable, sheath grounded, operated three-phase in delta, Mr. L. Lichtenstein* has made some calculations on which the following formula is based.

$$C = \frac{.0776 K}{\log_{10} \left\{ \frac{3 a^2}{r^2} \quad \frac{(R^2 - a^2)^3}{R^6 - a^6} \right\}}$$

The charging current per wire for a three-conductor cable equals:

$$\frac{2 \pi f C E D}{10^6 \sqrt{3}}$$

C equals capacity in microfarads per wire per mile.

D equals the length of the transmission in miles.

R equals the radius to the inner edge of the lead sheath.

r equals the radius of the conductor.

a equals the distance from the centre of the three-phase cable to the centre of one of the conductors.

*Elektrotechnische Zeitschrift, Feb. 11, 1904, Page 106.
" " " 18, " " 124.

E equals the impressed electromotive force between two conductors.

f equals the number of cycles per second.

K equals the specific inductive capacity of cable insulating material, which may be taken from table hereafter given.

TABLE XIV.

RELATIVE SPECIFIC INDUCTIVE CAPACITY OF CABLE DIELECTRICS AT 15 DEGREES CENT. (60 DEGREES FAHR.)

Air	1.0
India Rubber, pure	2.3
India Rubber, vulcanized	3 to 4
Rosin	2 to 3
Manilla paper, unsized	1.8
Paper and rosin oil	2.4
Jute and rosin oil	2.7
Shellac	3 to 4

The capacity and consequently the charging current of electric cables will vary decidedly with change of temperature, so that the values given in Table XIV, must be modified in accordance with the multipliers given in Table XV, in order to obtain a correct value of K to be used in the formulae given in the preceding pages.

The coefficients for saturated paper give results obtained from paper impregnated with soft compound. The coefficients given for rubber insulation are aver-

ages although the variations may be larger than indicated, depending on the constitutents of the rubber

*TABLE XV

INSULATION RESISTANCE AND ELECTROSTATIC CAPACITY TEMPERATURE COEFFICIENTS.

Temperature in degrees Fahr.	Saturated Paper Insulation		Varnished Cloth		Rubber Insulation	
	CO-EFFICIENTS		CO-EFFICIENTS		CO-EFFICIENTS	
	Insulation Resistance	S. I. Capacity	Insulation Resistance	S. I. Capacity	Insulation Resistance	S. I. Capacity
60	1.	1.	1.	1.	1.	1.
65	1.55	.95	1.38	.95	1.12 to 1.15	.99 to .98
70	2.36	.89	1.96	.90	1.25 " 1.30	.98 " .96
75	3.50	.82	2.75	.85	1.46 " 1.66	.96 " .93
80	5.50	.75	3.94	.79	1.68 " 2.26	.95 " .90
85	8.20	.67	5.50	.75	1.97 " 3.02	.93 " .88
90	12.7	.60	7.25	.70	2.29 " 4.10	.92 " .86
95	22.	.53	10.6	.64	2.70 " 5.60	.90 " .83
100	33.	.46	15.3	.60	3.10 " 7.60	.88 " .80
110	71.	.34	30.6	.50	4.40 " 15.00	.84 " .76
120	154.	.25	55.0	.42	6.40 " 26.00	.80 " .71
130	314.	.19	125.	.35	9.43 " 54.00	.76 " .65
140	636.	.14	262.	.31	13.00 " 108.00	.72 " .60

compound and whether or not the cables are lead covered. Capacity coefficients were determined by the discharge deflection method.

F. J. O. Howe states* he has found that the usual method of ascertaining capacity gives good commercial results in the case of rubber, gutta percha and jute cables; but in the case of paper cables, may give a value four, five or even more times too high by reason of variation in the relation of the leakage and charge currents. This is caused by the use of a softer and more oily impregnating compound employed for the thicker insulations required for higher voltages. Mr. Howe found that by applying high potential directly to the paper cable, the capacity of which it is desired to measure, having a hot wire ammeter in series, the capacity could in every case be accurately determined. Of course, the objection to the high voltage method is the danger to the operator and the necessity of running large machinery.

Mr. Howe's conclusions do not agree with those of American investigators who find that the measurements of capacity made by the ballistic galvanometer method give results 10 to 15 per cent higher than those obtained through the use of an ammeter and high potential, which method must of necessity include some small but real power losses. The ratio between capacity as determined by alternating currents and the capacity as measured by the discharge deflection method, usually becomes greater with increases in the per cent of Para used in the rubber compound. The ratio varying from .75 to .95 at 60 cycles, 60 degrees Fahr. The ratio with good paper insulation

* London Electrician, March 20, 1908.

is usually about .90 and with varnished cambric, from .50 to .75.* The smaller the ratio the greater is the liability of the dielectric to heat as the pressure stress is increased, which would indicate the disadvantage of using cambric for the higher voltages. The reason the capacity measurements made by a galvanometer increase relatively is due, Fisher states, to a polarizing action which occurs when the temperature of the insulation is raised.

It is known that the insulation resistance of rubber cables, at least, improves with time and tests indicate that the capacity of cables when newly made and measured on reels, is appreciably higher—as much as 20 per cent—than after they have been installed in ducts for some time.

British Insulated & Helsby Cables, Ltd., give the following information regarding capacity of three-phase, three-core cables insulated with paper, according to the British Standard Specification for a delta connected system. The British Engineering Standards Committee adopted the following radial thicknesses for jute or paper dielectrics of three conductor underground cables with neutral not grounded.

Size of Cable. Sq. In.	6,600 VOLTS		11,000 VOLTS	
	About Conductors	Belt	About Conductors	Belt
.025 – .075	.23 in.	.23 in.	.35 in.	.35 in.
.100 – .200	.24 "	.24 "	.36 "	.36 "
.250	.25 "	.25 "	.37 "	.37 "

* H. W. Fisher Proceedings, A. I. E. E., Vol. XXIV, Page 405.

*TABLE XVI.

CAPACITY OF THREE-CONDUCTOR CABLES.

Size of Cable		Voltage	Microfarads per Mile	
Sq. Ins.	C. M.		One Conductor against others and Ground	All Conductors tied together against Ground
.05	63,500	6,000	.299	.359
.10	127,000	"	.388	.465
.15	190,500	"	.440	.528
.20	254,000	"	.493	.592
.25	318,000	"	.528	.633
.05	63,500	11,000	.238	.285
.10	127,000	"	.290	.348
.15	190,500	"	.334	.400
.20	254,000	"	.361	.434
.25	318,000	"	.387	.465
.05	63,500	20,000	.176	.213
.10	127,000	"	.212	.254
.15	190,500	"	.238	.281
.20	254,000	"	.255	.306
.25	318,000			

*Copyright, B. I. & H. C., Ltd. Hand Book, 1907.

The above figures are safe for individual drum length, for a continuous cable of many drum lengths, the figures may be reduced by 20 per cent.

A comparison of the capacities of two large installations are here given, both because interesting and as showing the difference in similar dielectrics.

TABLE XVII.

CABLE CAPACITY MEASUREMENTS.

	New York Edison Co.		Interborough Rapid Transit Co.	
	Three-Conductor 250,000 c. m., 5/32+5/32-inch Insulation 1/8-inch Lead Sheath.		Three-Conductor, 000 B. & S. 7/32+7/32-inch Insulation 1/8-inch Lead Sheath.	
	Microfarads per Mile.		Microfarads per Mile.	
	Paper	Rubber	Paper A	Paper B
Between one Conductor and Ground	.19	.28	.139	.171
Between two Conductors	.06	.10	.043	.053

All the capacities given above, in microfarads, were calculated from measurements of charging current, made with an ammeter, high potential being applied directly to the cables. For the sake of clearness, it is assumed that between each conductor and lead sheath, or ground, there is a condenser C_1; i. e., there are three such condensers with a three-phase cable. Also between each conductor and its neighbor is a second condenser C_2 i. e., three such condensers making a total of six condensers in a three-core cable. The charging current per wire, per mile is then,

$$\frac{2 \pi f E C_1}{10^6 \sqrt{3}} + \frac{2 \pi f E C_2 \sqrt{3}}{10^6}$$

If C is assumed as a condenser between each conductor and the neutral point, grounded, of a three-phase cable, as in the equation on page 110, it can be shown that C equals $C_1 + 3C_2$ of the preceding formula. It is estimated that the capacity per conductor, to ground, C_1, of 330 miles of Interborough underground cables is 53.9 M. F., and similarly, the capacity between conductors, C_2, is 16.7 M. F., which with 11,000 volts, 25 cycles, will give a total charging current of 104 amperes per wire.

The condenser effect of cables, usually in series with the self-inductance of the generating system, is a condition tending to the creation of electrical oscillations. An interesting and startling display of the effects of this phenomena, which resulted not alone in the temporary shutdown of a large system but extensive damage to cables and apparatus, occurred in 1905 on the lines of the Manhattan Elevated Railway of New York City. The existing conditions were very thoroughly investigated from both the practical and theoretical standpoint by Mr. C. P. Steinmetz, and are ably discussed in his paper* "High Power Surges in Electric Distribution Systems of Great Magnitude."

For information regarding the theory and experience with and advantages of grounding the neutral of a high

* Proceedings A. I. E. E., vol. XXIV., page 297.

tension system, we would refer the reader to the papers "The Grounded Neutral"* and "Experience with a Grounded Neutral on the High-tension System of the Interborough Rapid Transit Company,"† and the discussions following these papers. It will be found that both theory and practice differ widely in this connection; some of the largest systems operating without grounded neutral and other systems in the same city using the grounded neutral.

Reactance. As compared with continuous currents, every conductor offers either increased or decreased opposition to the flow of alternating currents, due to inductance, "skin effect," and capacity. The opposition to the flow of alternating currents in a conductor, aside from that due to ohmic resistance, is known as reactance, and equals $2 \pi f L$, when caused by inductance, and $\frac{1}{2 \pi f C}$ when caused by capacity,

f equals the cycles per second.

L equals the inductance in henrys.

C equals the capacity in farads.

In a series circuit the algebraic sum of the inductive and capacity reactances, which oppose one another, gives the total reactance of the circuit.

When induction and capacity reactance are connected in parallel, the resultant current is the alge-

* F. G. Clark, Proceedings A. I. E. E., vol. XXVI., page 1597.

† G. I. Rhodes, Proceedings A. I. E. E., vol. XXVI., page 1605.

braic sum of the currents taken by the respective reactances, which currents are in opposition.

Impedance. Impedance is the total opposition to the flow of an alternating current in a conductor due both to the ohmic resistance and the reactance and equals, for a series circuit,:

$$\sqrt{R^2 + \left\{2 \pi f L + \frac{1}{2 \pi f C}\right\}^2}$$

Theoretical deductions as to the impedance of high-tension underground cable are complicated by reason of the many variables such as capacity of the dielectric, distance between conductors, diameter of conductors, diameter of completed cable, etc., so that tables are much more convenient and fully as correct as far as practical results are concerned, because slight variations from theoretical assumptions, which are liable to occur in manufacture, result in as great differences between theoretical deductions and actual measurements as between tables and measurements. On the following page is given a table showing the impedance for three-conductor cables for potentials not exceeding 20,000 volts.

The following figures are based on the use of varnished-cambric insulation, but the values are practically the same for other types of insulation of the same thickness as specified in the table. The conductivity is based on pure copper at 75 degrees Fahr. (and are approximately correct for 98 per cent conductivity of

copper at 65 degrees Fahr.), with an allowance of 3 per cent for spiral path of conductors and 60 cycles per second.

***TABLE XVIII.**

APPROXIMATE OHMIC RESISTANCE AND IMPEDANCE OF THREE-CONDUCTOR CABLES AT 60 CYCLES.

Size B. & S.	Resistance Ohms per Mile	Impedance Ohms Per Mile — Working Voltage				
		5,000	7,000	10,000	15,000	20,000
		Total Thickness of Insulation, Inches				
		$\frac{3}{32} \times \frac{3}{32}$	$\frac{4}{32} \times \frac{4}{32}$	$\frac{5}{32} \times \frac{5}{32}$	$\frac{13}{64} \times \frac{13}{64}$	$\frac{16}{64} \times \frac{16}{64}$
2	.850	.859	.863	.867	.872	.884
1	.674	.696	.700	.706	.712	.724
0	.535	.547	.552	.558	.565	.580
00	.424	.439	.444	.452	.460	.478
000	.336	.352	.357	.365	.374	.396
0000	.267	.283	.288	.296	.306	.332
250,000	.227	.245	.252	.261	.272	.299
300,000	.188	.210	.217	.227	.241	.270
350,000	.161	.187	.194	.204	.217	.250
400,000	141	.166	.174	.185	.199	.234
450,000	.127	.148	.156	.167	.182	.221
500,000	.113	.137	.144	.156	.172	.212

Skin Effect. Skin effect, or the unequal distribution of current in the cross-section of a wire, is a phenomena which develops in connection with alternating currents

only. The effect increases with frequency and with the diameter of the conductor; but with commercial frequencies now used and the size of conductors employed in high-tension work, "skin effect" is practically of little importance; for copper conductors of 300,000 c.m. and frequencies not exceeding 60 cycles per second, the "skin effect" increases the ohmic resistance less than 1 per cent. Although an aluminum conductor for the same resistance is considerably larger than a given copper conductor, the aluminum conductor will have no greater "skin effect" than the copper conductor.

Lord Kelvin investigated this phenomena of "skin effect" and made some calculations, upon which many subsequent tables have been based; although experimental verification of them by later investigators, seems to be lacking.

The calculations by which the formula for determining "skin effect" is derived, is too complex to be included in this volume. For non-magnetic conductors the formula is as follows:

$$*R_c = R + \frac{1}{3R}\left(\frac{.0000195\ f\ D}{10^9}\right)^2 - \frac{4}{45\ R^3}\left(\frac{.0000195\ f\ D}{10^9}\right)^4$$

Rc equals the resistance to alternating currents.

R equals the resistance to continuous currents.

f equals the cycles per second.

D equals the length of the conductor in miles.

The skin effect with magnetic conductors of the usual size is so great as to prohibit their use for ordinary commercial alternating currents.

*Based on formula in Gerard's Leçons sur l'Electricité.

CHAPTER VIII.

TESTING OF CABLES.

Summary. It is pretty generally agreed that it is impossible to definitely determine the merits of a dielectric intended for high-tension work by one set of tests—electrical, mechanical or physical. Any set of specifications should include all the three classes of tests named, and this is particularly true with reference to rubber insulation.

In Chapter IV. on "Cable Insulation," under the respective paragraphs referring to the various types of dielectrics employed, information has already been given regarding most of the requirements that should be covered in order to insure high-grade, high-tension insulation. The information given related more particularly to chemical, physical and mechanical tests, while that which has been omitted relates to electrical tests, which include,

(a) Measurements of insulation resistance.

(b) Determination of the dielectric strength of the insulating coating by means of a disruptive discharge.

Ohmic and Puncture Tests. Quoting from the Standardization Rules of the A. I. E. E.,

> "The ohmic resistance of the insulation is of secondary importance only, as compared with

the dielectric strength, or resistance to rupture by high voltage. Since the ohmic resistance of the insulation can be very greatly increased by baking, but the dielectric strength is liable to be weakened thereby, it is preferable to specify a high dielectric strength rather than a high insulation resistance. The high-voltage test for dielectric strength should always be applied."

Of all tests suggested, the puncture test is the most important. In the early days of cable manufacture, high insulation resistance as measured in megohms, was considered the essential of good cable construction, and it is still admitted this is an important guide. But the ohmic resistance of insulations, particularly rubber, varies greatly due to differences in their composition, change of temperature, or ofttimes to a change in the testing voltage, particularly with poorer quality of insulation, even when all other factors remain the same.

Even a moderate rise in the temperature of rubber, for example, very rapidly reduces its resistance as measured in megohms; but a greater rise effects the insulation comparatively slowly, in the way of decreasing its perforation point, unless high temperatures, say 100 to 150 degrees Cent., for this particular material, are continued for some time, when possible chemical changes may take place. So, while this considerable change of resistance with moderate increase of temperature is of little importance in practical work,

because the leakage loss will be an inappreciable amount of the energy being transmitted, high temperatures will ruin all cable insulations.

It is not difficult to obtain high megohm measurements in inferior grades of insulation, and one thousand million megohms per cubic inch for the best grades of rubber is easily obtainable. Cables may be accepted as satisfactory from the standpoint of insulation resistance measurements, provided rubber (30 per cent Para) shows from 1,000 to 2,000 megohms, and paper or cambric, 20 to 50 megohms per mile, at 15 degrees Cent. (60 degrees Fahr.), after 12 hours immersion in water, with one minute's electrification preferably with 500 volts; of course, paper and cambric-insulated cables must not be immersed in water until after being sheathed with lead. The ohmic measurements should be made after the puncture tests. The rate of change of resistance with temperature, for the best rubber compounds, is said to be about 2.5 per cent per degree Fahrenheit.

While it is important that the resistance of a cable installed be known and recorded as a matter of reference in locating faults, and while it is generally recognized that an insulation which will withstand high perforation tests will usually show satisfactory ohmic resistance, it is acknowledged that insulation resistance gives little indication of disruptive strength. For example, in multiple conductor cables for high voltage, the jute filling usually more or less separates the insulation from the sheath, so that resistance tests

may show up exceedingly well; but the jute, of course, will not withstand high puncture tests.

As far back as 1899, when drawing specifications for the 25,000-volt St. Paul cables, the writer waived all resistance insulation tests, depending rather upon the perforation tests to determine the excellence of the insulation. Modern practice concurs in these views and megohms required in high-tension specifications have been much reduced or omitted, as insistence on high ohmic requirements is likely to result in the production of a non-flexible and brittle insulation.

A cable in practical use may be stressed to once and a half or twice normal voltage by failure to synchronize generators or the running away of a governor; but is only likely to receive for brief periods, excessive voltages which may be caused by surges or something of that sort. Fortunately, the ability of a cable dielectric to withstand puncture is a factor not alone of the stress applied but also of the duration of that stress; consequently, from two to two and a half times normal voltage as a time-test, with five to eight times normal voltage with momentary-test, should seem to meet the requirements of practical working. For high-voltage work, the present consensus of engineering opinion demands a 5-minute puncture test at two and a half times normal working voltage, at the factory, and twice normal voltage after installation, without regard to the size of the conductor; but higher momentary tests have not yet been agreed upon. Reduced potential tests for 30 minutes or more, are not

less valuable than the 5-minute test; a time-test of days or weeks would give a still better indication of the durability of the dielectric.

Too severe high potential tests may strain or weaken some of the less strong particles of the insulating material, which may later break down under the normal working pressure; hence, moderate increase of potential should only be applied for time-tests with higher momentary tests upon cables completely installed. Further, tests for perforation should be applied on pieces 10 or 15 feet in length, cut off for the purpose of testing. Cables will momentarily withstand much higher potentials than those which may be applied constantly. For example, a cable that will withstand double normal voltage may conservatively be required to withstand instantaneous applications of five times the normal potential. In making potential tests, ample generator or transformer capacity must be provided, otherwise the charging current may distort the electro motive force wave and reduce the applied voltage. The American Institute of Electrical Engineers recommends the use of apparatus having four times the kilowatt capacity of the apparent energy required in making test.

All tests are based on the use of a sine wave of electro-motive-force. The wave form of the generator is particularly important, if the circuits supplied are constituted of cables, as sharp peak or jagged waves tend to produce oscillations or resonance; consequently the designing engineer should see to it that the

generating apparatus, whether to be used for testing or operating, is properly designed to insure a sine wave of electric-motive-force.

Maintenance of periodic inspections and moderate tests are much more vital to the continued operation of cables than mere test at abnormally high voltage. An instance could be cited where cables tested satisfactorily up to 90,000 volts before breaking down, but which later gave trouble under regular 11,000-volt operation. It is possible to so treat some insulations as to insure their withstanding high puncture tests for a short time, although the same cable will not operate continuously and successfully at lower voltages. In making high-voltage puncture tests, it is desirable to avoid the use of a spark-gap, as a measure of the potential being applied, because the breakdown of the air gap causes surges which may result in the piling up of potential above what is desired and consequent weakening or damage to the insulation.

It is not definitely known just how important the element of time is in connection with breakdown tests of cables. Just what relation there is for the different dielectrics between potentials applied and the length of time of this application, is not known.

Most tables of puncture tests proposed that have thus far appeared in print, are very conservative. The tables, prepared for example, by Fisher,* Langan,† Clark,‡ the Engineering Standards Committee of

*Proceedings A. I. E. E., Vol. XXIV., Page 414.
† " " " XXV. " 200.
‡ " " " XXV. " 212.

England—except on the basis of their higher puncture tests which are about three times working potentials—and probably also the Engineers' Association of Wire Manufacturers, give test voltages too conservative for commercial conditions; their use would result in the requiring of insulations unnecessarily thick and expensive for minimum investment with reasonable factor of safety, particularly for the high voltages. Examination of the table on page 28 will show that at the higher voltages, at least, operating plants are not requiring insulations as heavy as called for by the tables above referred to. Some cables used for the lower voltages included in this table of installations, have intentionally been provided with insulations sufficiently heavy to permit doubling the working voltage, thus unfairly indicating a larger factor of safety than will be actually the case.

Chapter IX.

COSTS.

Total Costs. The complete cost of a system for underground distribution of electric energy is made up of two entirely independent components—one the cost of the excavation and subsurface construction, and the other the cost of the conductors properly insulated, mechanically protected and installed. The type of subsurface structure varies from simply a trench in which the electrical cables are buried to fireproof conduits, embedded in cement, which connect manholes spaced perhaps 400 feet or 500 feet apart, the manholes being, in some cases, as large as a small room and costing several hundreds of dollars each. The proper type of underground structure varies for different installations, depending on the investment allowable, the protection required and the desirability of being able to withdraw cables without disturbing the surface of the ground. In American cities conditions more commonly require the construction of conduit systems, which are usually of bituminized wood-fibre or the more costly vitrified clay ducts, laid in Portland cement. Owing to the difference of opinion among engineers as to the proper depth below the surface conduit should be laid, the mixture of cement to be used, the thickness of the concrete walls enclos-

ing the conduits, the difference in type and size of manholes, and the varied costs of excavation due to difficulties in local conditions, such as traffic, sewer, water and gas pipes, rock or water-soaked material, the cost of labor, and particularly the widely varying expense of similar work owing to the varying ability of those in charge, it is impracticable to obtain average figures for conduit construction cost. The ducts vary from about 9 cents per foot of length, under most favorable circumstances, up to $2.00 or $3.00 per foot, under most exacting conditions. Similarly, manholes may cost from a few dollars up to five or six hundred dollars each, depending on size, type and conditions of installation. The only safe method of estimating the cost of conduit construction for any given locality, is by comparison, item by item, with due allowance for differences, with costs in another given locality.* On the other hand, the price of underground cables will be approximately the same at a given time, disregarding the easily ascertainable freight rates, in any part of the United States.

Cable Costs. The cost of high-tension cables will vary somewhat from time to time, depending on the

* For detail figures on different methods and varying costs of conduit construction for electric cables, see Foster's Electrical Engineer's Pocketbook, fifth edition, page 301; the Electrical Age, November, 1908, Page 260; Proceedings National Electric Light Association, 1904, Appendix A, following page 577; Proceedings International Electric Congress of St. Louis, 1904, vol. II., page 671.

price of materials and labor; but this variation will be considerably less than might be expected owing to the fact that the cost of the cable of a particular type is made up of different items, variations in the cost of which, more or less, offset one another. For example, the present base price of copper is, say 14½ cents, the highest price having been 27 cents, and the market price of rubber is about $1.10 a pound, the highest price having been only $1.30 a pound; similarly, the price of lead at present is about 4½ cents per pound, the highest price having been 6 cents per pound; paper costs 8 cents per pound, having cost as high as 10 cents per pound; the cost of labor is about as high now as at any time, although the efficiency is somewhat better. From these figures it will be seen that for a foot of three-conductor 0000 25,000-volt rubber-insulated cable, which at present prices contains about 28 cents of copper, 23 cents of lead and 140 cents of rubber, out of an assumed total cost of 270 cents per foot; whereas, if the maximum prices given above are all used, the total cost is 326 cents per foot, or an increase of only 56 cents, or about 20 per cent, as between present prices and all of the maximum prices which have been reached.

For the purpose of investigating the varying costs of high-potential cables insulated with paper, cambric and rubber, and so-called "graded" insulation, prices were obtained from several of the largest and most reliable manufacturers of high-tension cables. As the quotations were made about the first of October, 1908,

it may be assumed that the prices named were based on the cost of raw material being about as given in the first part of this section. The prices asked were on cables designed for normal working potentials of 11,000, 25,000, 35,000 and 50,000 volts, with conductors of No. 4 and No. 0000 B. & S. gauge. Less recently a price was secured on a 50 sq. mm., 75,000-volt cable with "graded" insulation. The 11,000, 25,000 and 35,000-volt cables were to be built with three conductors, each separately insulated and then laid up and enclosed in a jacket of the same insulating material, the whole being covered with 1/8-in. lead containing 3 per cent tin. The 50,000 and 75,000-volt cables were to be built with a single conductor properly insulated and covered with a similar lead sheath. All of the prices quoted were f. o. b. factory, and the curves given hereafter were drawn by plotting the various prices quoted for the several characters of insulation, at different voltages, and drawing lines, to represent the average, through the points as plotted, no allowance being made for transportation—a value easily ascertainable for any given locality—or for the cost of connecting and drawing the cables into ducts, which may be taken at from 8 cents to 10 cents per foot per cable. I assume it is fair to conclude that curves obtained in this way correctly indicate the cost of cables at intermediate voltage, which may be read from the curves.

SPECIFICATIONS FOR THREE-CONDUCTOR CABLES WITH AVERAGE OF PRICES PER FOOT.

Each conductor separately insulated and laid up with jute fillers to make round, the whole covered with a jacket of insulating material, outside of which there is to be 1/8-in. lead sheath, lead to contain 3 per cent tin. No. 0000 conductors to be stranded; No. 4 conductors to be solid. All cables to be tested for five minutes on twice normal working voltage, after installations.

	11,000-VOLT		25 000-VOLT		35 000-VOLT	
	No. 4	No. 4-0	No. 4	No. 4-0	No. 4	No. 4-0
Paper	$0.49	$1.03	$0.87	$1.47	$1.15	$1.76
Cambric	0.77	1.49	1.36	2.30	1.80	2.87
Rubber	1.30	1.78	1.80	2.66	2.16	3.30

SPECIFICATIONS FOR THREE SINGLE-CONDUCTOR CABLES WITH AVERAGE OF PRICES PER FOOT.

Each single-conductor cable insulated and sheathed with 1/8-in. lead, lead to contain 3 per cent tin. No. 0000 conductors to be stranded; No. 4 conductors to be solid. All cables to be tested for five minutes at twice normal working voltage, after installation.

	50,000 VOLT		75,000 VOLT
	Three No. 4	Three No 4-0	Three 50 sq mm.
Paper	$3.18	$4.12	....
Graded	3.75	4.95	$6.78
Rubber	6.00	6.90	....

The prices submitted by the different manufacturers on the lower voltage cables did not differ much among themselves, but as the voltage increased the differences were more marked. There was only one quotation on 75,000-volt cables; all but one of the manufacturers requested to do so bid on 50,000-volt cable; all requests for prices at the lower voltages were complied with, and it is fair to assume that all reliable, experienced cable manufacturers stand ready to furnish and guarantee three-conductor cables, as large as No. 0000 B. & S. for tensions as high as 35,000 volts.

COSTS OF HIGH-TENSION UNDERGROUND ELECTRIC CABLES.

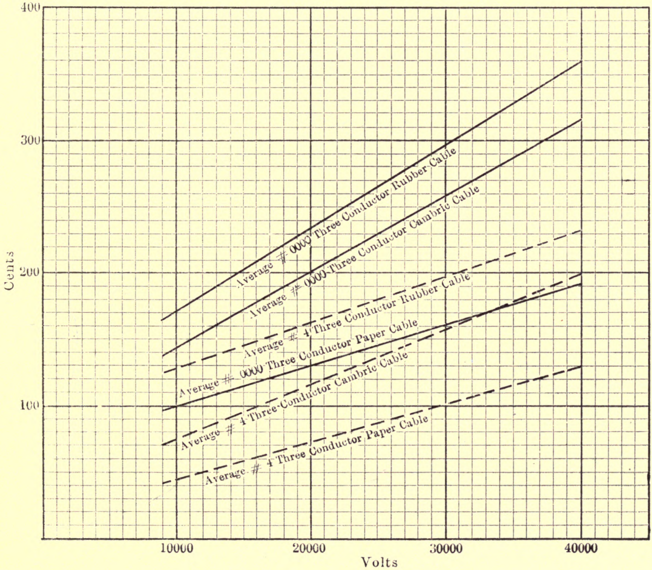

FIG. 4